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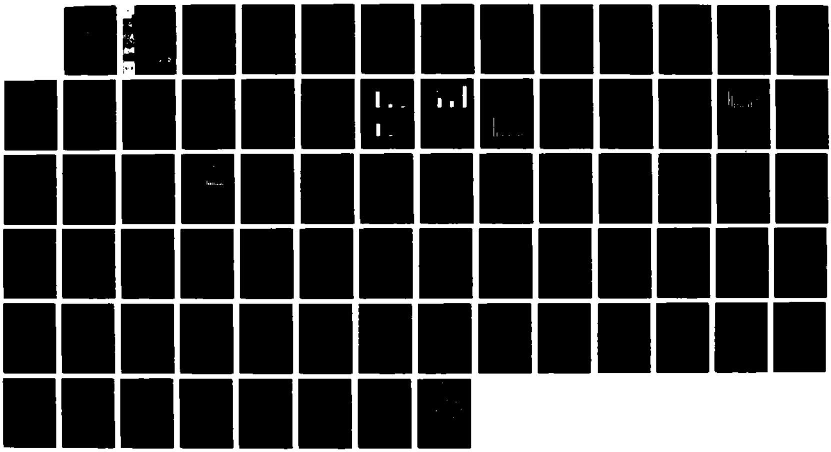

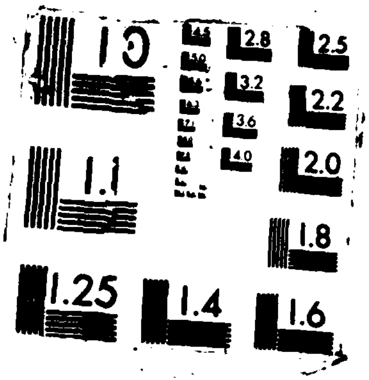
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US Army Corps of Engineers

TECHNICAL REPORT EL-87-9

NEW YORK WATER SUPPLY INFRASTRUCTURE STUDY

VOLUME III: THE BRONX AND QUEENS

by

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Environmental Laboratory

DEPARTMENT OF THE ARMY
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This report describes an evaluation of the water distribution system in the Bronx and Queens, with special emphasis on water main breaks. The report presents a statistical analysis of breaks by sizes, causes, and season, among other considerations. It also examines trends in break rate with age of pipe and determines that the pipes are deteriorating with time, although these effects are masked somewhat by different laying practices and pipe materials.

Criteria for determining which pipes should be replaced are developed. These criteria are based on a number of factors, most important of which are break cost, replacement costs, rate of pipe deterioration, and interest rate. The actual break rates of potential pipe replacement projects are compared with the critical break rate to determine which pipes should be replaced. Listings of replacement projects, and their costs, are then presented.

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PREFACE

This report describes a study conducted by the US Army Engineer Waterways Experiment Station (WES) for the US Army Engineer District (USAED), New York, under Intra-Army Order No. NYD 86-0015. The USAED, New York, was requested by the State of New York to perform this work, in accordance with authorization in Section 214 of Public Law 89-298, and later under Section 22 of Public Law 93-251.

The study was conducted at WES by Dr. Thomas M. Walski of the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), and Mr. Roy Wade of the Water Supply and Waste Treatment Group (WSWTG), EED, EL. They were assisted by Mr. John W. Sjostrom of WREG and Mr. Anthony Lewis of WSWTG.

The work was monitored by Mr. David Schlessinger of the Planning Division of the USAED, New York, under the supervision of Mr. Tom Pfeifer.

This is the third volume of a series on the New York City water supply infrastructure. The first two volumes reported on the boroughs of Manhattan and Brooklyn, respectively, and were prepared for the USAED, New York, by Betz, Converse and Murdoch, Inc. (BCM). Volume IV will address the borough of Staten Island. A summary report for New York City will be presented as Volume V.

The pipe break data files used in this study were prepared by BCM under previous contracts with the USAED, New York. Mr. Ron DeRosa of BCM provided these files, as well as other assistance.

The point of contact with the Department of Environmental Conservation of the State of New York was Mr. Howard Pike. The point of contact with the New York City Department of Environmental Protection was Mr. Edward C. Scheader, Deputy Director of the Bureau of Water Supply. Additional support was provided by Mr. Martin Engelhardt, Chief of Planning and Programs; Mr. Richard Siegel, Chief of System Operations; and Mr. Richard Gainer, Chief of Field Operations. Mr. Doug Greeley of the Field Operations Division prepared most of the data provided by the Bureau of Water Supply.

Technical reviews of this report were provided by Mr. M. J. Cullinane of the WSWTG and Dr. James W. Male of the Civil Engineering Department of the University of Massachusetts under an Intergovernmental Personnel Act agreement. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

Acting Chief of the WREG was Mr. F. Douglas Shields, Jr.; Chief of the WSWTG was Mr. Norman R. Francingues. The study was conducted under the general supervision of Dr. Raymond L. Montgomery, Chief, EED; Dr. John W. Keeley, Acting Chief, EL; and Dr. John Harrison, Chief, EL.

COL Dwayne G. Lee, CE, was the Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

This report should be cited as follows:

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (force) per square inch	6.894757	kilopascals

NEW YORK WATER SUPPLY INFRASTRUCTURE STUDY

THE BRONX AND QUEENS

PART I: INTRODUCTION

Background

1. Concern over the condition of the Nation's infrastructure has increased in recent years with the realization that many of the components of the infrastructure (e.g., roads, pipes, treatment facilities) are deteriorating with time. Since they are buried underground and fail so seldom, deterioration of water distribution systems has often been ignored. The results of past deferred maintenance are now being realized in the form of increasing expenditures for pipe break repair and associated damages, excessive loss of water, decreased hydraulic carrying capacity, more frequent water outages, and increased risk of system contamination.

2. The cost to completely replace the water supply infrastructure is prohibitively large and such a project is unnecessary since most facilities are in good condition. Wise expenditure of funds for infrastructure improvement therefore involves identifying weak components of water systems--those for which replacement costs will be less than repair costs--and replacing or rehabilitating them.

3. Because of this concern over the water supply infrastructure, the State of New York asked the US Army Engineer District (USAED), New York, to conduct an investigation of the water supply infrastructure in New York City. Since the City's distribution grid has good carrying capacity and, in recent years, the Bureau of Water Supply has been conducting a leak detection program, the Corps of Engineers' work has focused on problems of pipe breaks. Studies of the water distribution systems in Manhattan and Brooklyn have been conducted by Betz, Converse and Murdoch, Inc. (USAED, New York 1980, 1984). This report, which covers the Bronx and Queens, is the third volume in the series. A report on Staten Island and a summary report are scheduled to follow.

Purpose

4. This report describes the results of an investigation of the condition of the water distribution system in the Bronx and Queens with primary emphasis on water main breaks. The study purpose is to examine historical data and an inventory of the distribution system to determine ways of better managing the system. This includes statistical analysis of pipe break data and identification of water mains (or groups of mains) for which replacement or some other remedial action is desirable.

Overview

5. There were two major thrusts to this study: (a) statistical analysis, and (b) identification of replacement projects.

6. In Part II, an inventory of the distribution systems is presented, followed by an analysis of types and causes of breaks and seasonal trends. The most important analysis consists of identifying temporal trends in pipe breaks and determining the rate of deterioration of water mains.

7. Part III begins with a projection of future water main replacement costs. Replacement criteria, as developed in Appendix A, are then presented. Pipe replacement projects are identified next, with sections on the considerations for both large and small pipes. Budget estimates of costs to replace water mains are then presented. Part IV presents a summary and the study conclusions.

8. Development of pipe replacement criteria involves some mathematics. For convenience, detailed discussion of how the replacement rule was derived is presented in Appendix A. The replacement rule can be used to give the year in which pipes with a given break rate should be replaced, or conversely, the critical break rate of pipes to be replaced by a given year. Development of cost data to be used in the replacement rule is also described in Appendix A. In addition to this report, maps showing pipe breaks in the Bronx and Queens were developed and transmitted to the New York City Bureau of Water Supply.

9. This report differs from the Manhattan and Brooklyn reports described earlier in that less material is presented on the general causes of pipe breaks and the magnitude of infrastructure problems. Readers interested in such information are referred to the previous reports (USAED, New York

1980, 1984), a report on the City of Philadelphia, Pa. (Weiss et al. 1985), and work by Walski (1984). This report, in accordance with the wishes of the Bureau of Water Supply, focuses on identification of specific pipe replacement projects as opposed to indicating areas or census tracts with higher break rates. Such information was felt to be more useful than duplicating some of the more general information contained in earlier reports.

PART II: STATISTICAL ANALYSIS OF PIPE BREAK DATA

10. Analyzing the history of pipe breaks in the Bronx and Queens provides some insights into why pipes break and suggests some remedial measures for addressing the cause of the breaks. The data also indicate trends in pipe breakage. Such information is needed in the economic analysis presented in Part III.

11. The following section presents an inventory of water mains in the Bronx and Queens. This is followed by a description of the effects of a variety of factors (e.g., diameter, weather, pipe thickness) on the break rate. Finally, several different rates of increase of pipe breakage are determined.

Inventory of Water Mains

12. Before analyzing pipe break data, it is useful to inventory water system components. This is especially important because it is incorrect to simply compare numbers of breaks between one category (size, location, material) of pipe and another. Instead, one should compare the break rate, which is the number of breaks per unit length per unit time. For this study, the break rate will be expressed in units of breaks per year per mile.

Inventory by diameter and time period laid

13. It is necessary for subsequent analyses to know the length of in-place pipe by diameter and time period laid. For this study, calculations were simplified by dividing time into 5-year intervals (pentads) and assigning the date the pipe was laid to one of these pentads.

14. The data base used to prepare the water main inventory was the New York City Fixed Assets Accounting System Master File prepared by Earnst & Whinney and maintained by the City. Data on water mains in the Bronx and Queens were extracted from that file to create a water main inventory file, from which Table 1 for the Bronx and Table 2 for Queens were derived.

15. In both the Bronx and Queens, the distribution system is composed primarily of 8- and 12-in.* pipes, with these diameters accounting for just

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

Table 1

Inventory of Bronx Water Mains

Installation Date	Length, ft, of Indicated Pipe Diameter, in.									Total		
	6	8	12	16	20	24	30	36	48	Feet	Miles	Percentage
0-1869	0	0	40	0	0	0	0	0	0	40	0.01	0.00
1870-1874	0	0	1,047	0	0	0	0	0	0	1,047	0.20	0.02
1875-1879	2,912	1,514	3,434	0	1,119	0	0	0	0	8,979	1.70	0.20
1880-1884	2,219	130	5,772	0	1,079	0	0	470	0	9,670	1.83	0.21
1885-1889	5,180	162	19,046	0	1,784	0	0	950	0	27,122	5.14	0.59
1890-1894	9,222	804	21,762	0	735	0	0	5,116	256	37,895	7.18	0.83
1895-1899	23,387	1,891	35,322	0	8,534	0	0	3,303	5,772	78,209	14.81	1.71
1900-1904	57,237	7,618	64,246	1,000	10,736	0	200	11,921	15,544	168,502	31.94	3.69
1905-1909	45,490	11,941	195,200	6,643	36,401	0	0	2,359	25,625	323,659	61.30	7.07
1910-1914	16,105	58,315	172,855	283	48,459	0	0	17,473	13,019	326,509	61.84	7.14
1915-1919	4,688	32,131	37,851	264	3,651	499	2	766	1,586	81,438	15.42	1.78
1920-1924	27,025	302,207	116,283	7,621	7,510	0	150	12,339	1,305	474,440	89.88	10.37
1925-1929	34,940	426,909	144,610	1,016	44,000	800	588	11,903	3,056	667,822	126.48	14.60
1930-1934	23,582	187,459	114,859	458	15,255	6,151	0	2,814	27,273	377,851	71.56	8.26
1935-1939	14,083	132,684	140,324	2,325	28,579	1,033	339	8,778	16,507	344,652	65.33	7.54
1940-1944	4,109	56,760	82,226	0	17,544	122	0	3,690	3,074	167,525	31.73	3.66
1945-1949	3,961	50,675	62,859	0	6,438	0	0	40	1,023	124,996	23.67	2.73
1950-1954	6,601	84,105	105,642	879	27,248	1,075	0	10,500	5,505	241,555	45.75	5.28
1955-1959	7,177	76,082	111,577	0	13,366	0	0	1,374	2,740	212,316	40.21	4.64
1960-1964	6,028	93,339	136,450	148	29,576	733	407	998	1,902	269,581	51.06	5.89
1965-1969	3,909	68,383	129,276	716	39,310	960	0	3,032	29,130	274,716	52.03	6.00
1970-1974	6,594	40,332	82,314	1,848	36,019	275	0	757	1,206	169,345	32.07	3.70
1975-1979	1,597	38,683	61,705	70	16,171	0	0	305	642	119,173	22.57	2.60
1980-1985	0	19,857	35,502	322	12,210	0	0	0	0	67,891	12.86	1.48
Total, ft	306,046	1,691,981	1,880,202	23,593	405,724	11,648	1,686	98,888	155,165	4,574,933		
miles	58.0	320.5	356.1	4.5	76.8	2.2	0.3	18.7	29.4		866.5	
Percentage	6.7	37.0	41.1	0.5	8.9	0.2	0.0	2.2	3.4			100

Table 2

Inventory of Queens Water Mains

Installation Date	Length, ft, of Indicated Pipe Diameter, in.										Total		
	6	8	12	16	20	24	30	36	48	60	72	Feet	Miles	Percentage
Pre-1915	228,429	966,484	612,640	74,491	125,051	25,230	48,502	37,772	831.5	15,040	14,961	2,231,715	422.67	27.6
1915-1919	1,700	85,886	21,860	1,210	6,230	590	180	0	0	0	0	117,656	22.28	1.4
1920-1924	148,604	426,084	91,470	15,485	22,130	13,060	15,011	460	5,860	5,042	520	743,726	140.86	9.2
1925-1929	29,489	691,731	150,282	10,700	29,772	3,105	10,765	660	1,575	13,830	271	942,180	178.44	11.6
1930-1934	8,650	291,249	72,288	4,540	50,630	9,260	5,850	0	34,316	8,385	0	485,168	91.89	6.0
1935-1939	10,501	414,239	189,465	15,675	23,900	2,260	6,955	2,620	24,692	6,215	0	696,522	131.92	8.6
1940-1944	2,246	212,135	109,918	8,720	33,276	6,760	0	0	14,891	0	0	387,946	73.47	4.8
1945-1949	3,890	248,141	144,407	760	14,730	0	530	3,220	10,867	290	0	426,835	80.84	5.3
1950-1954	4,190	275,822	207,159	0	52,651	1,050	460	730	4,180	5,385	33,087	584,714	110.74	7.2
1955-1959	3,810	184,187	132,742	0	25,413	290	60	805	13,381	17,085	0	377,773	71.55	4.7
1960-1964	2,660	159,601	87,584	0	13,720	280	380	880	5,540	0	18,811	289,456	54.82	3.6
1965-1969	2,710	115,331	135,193	0	20,295	0	210	0	820	500	12,740	287,799	54.51	3.6
1970-1974	740	67,789	74,816	0	13,022	140	260	920	0	140	7,445	165,272	31.30	2.0
1975-1979	4,700	73,021	64,605	0	30,120	390	840	0	260	0	70	174,006	32.96	2.1
1980-1985	25	86,214	58,253	0	35,477	0	0	0	0	0	0	179,969	34.09	2.2
Total, ft	452,344	4,297,914	2,152,682	131,581	496,417	62,415	90,003	48,067	199,497	71,912	87,905	8,090,737		
miles	85.7	814.0	407.7	24.9	94.0	11.8	17.0	9.1	37.8	13.6	16.6		1532.2	
Percentage	5.6	53.1	26.6	1.6	6.1	0.8	1.1	0.6	2.5	0.9	1.1			100

over three-quarters of the pipes laid. In the early years of the system, a significant length of 6-in. pipe was laid. However, since World War I, 6-in. pipe has been laid sparingly, and in recent years, the policy of the Bureau of Water Supply has been to replace 6-in. mains with larger mains. This replacement policy was adopted both to improve hydraulic carrying capacity of the system and to reduce pipe breakage since 6-in. pipe tends to be more prone to breaks than larger pipe sizes, as will be shown later in this report.

16. The Bronx inventory dates back to roughly 1870, while the Queens inventory's first category is "pre-1915." This designation is due apparently to the fact that individuals who prepared the fixed asset file simply entered "1910" whenever they were not certain of the year in which an old pipe was laid. This was only one of a number of inconsistencies in the data file. Other problems included inconsistencies such as some 6-in. pipes being coded as 60 in. and pipe segments ending at intersections of streets that did not intersect.

17. The total mileage of pipes listed in the fixed assets inventory differs by roughly 10 percent from the "miles in place" listed by the Bureau of Water Supply in their reports. The Bureau of Water Supply indicates it has 940.3 and 1,776.7 miles of pipe in the Bronx and Queens, respectively, as of 31 December 1985. Both values are significantly higher than the values of 866.6 and 1,532.3 miles for the Bronx and Queens listed in the Tables 1 and 2 (as taken from the Fixed Assets Accounting System). The reason for this is not certain but may have to do with inclusion of hydrant laterals and water mains smaller than 6 in. in the Bureau of Water Supply's inventory but not in the Fixed Assets Inventory. If this is the case, the Fixed Assets mileage should be used for calculating break rates because the pipe break data file used in this study contains only main breaks and not service line, hydrant lateral, or fire line breaks.

18. One possible explanation for the confusing inventory data in Queens is that a large portion of the pipe installed in Queens was not laid by the New York City Bureau of Water Supply. Instead, it was laid by other utilities which have since been taken over by the Bureau of Water Supply. The system operated by the Citizen's Water Company was taken over in 1922, while the Utilities and Industries Corporation system was taken over in 1974. These acquisitions involved 198.2 and 121.1 miles, respectively. Several other small utilities were also absorbed into the New York City System. Apparently,

records on the dates on which the pipes were installed were not available, and therefore, for the purpose of the Fixed Assets Inventory, these pipes were treated as having been laid in 1910.

19. The inventory of pipes in the Queens distribution system includes only those pipes belonging to the New York Bureau of Water Supply and does not include pipes belonging to the Jamaica Water Company, which operates in the east-central portion of Queens (roughly between Union Turnpike, Southern Parkway, Van Wyck Expressway, and the Nassau County line).

20. In general, the largest burst of construction activity in the boroughs occurred during the 1920's. In recent years, only about 2 percent of each borough's system is being laid each pentad. Most of this pipe laying consists of replacing old 6-in. pipes and old mains associated with street rehabilitation.

21. The Bureau of Water Supply tries to limit the number of different diameter pipes to as few standard sizes as possible in order to reduce the required inventory of replacement pipes and fittings. These sizes are 8-, 12-, 20-, 36-, 48-, 60-, and 72-in. diameters. There are very few 16-, 24-, 30-, and 54-in.-diam pipes. No 10-, 14-, 18-, or 42-in.-diam pipes are listed in the inventory.

Pipe materials

22. Most of the smaller sized pipes (<48 in.) laid before 1970 a cast iron. Since 1971, the cast iron mains have been replaced by ductile iron pipe. Since 1930, iron mains have been cement mortar lined to prevent internal corrosion. The largest pipes in the systems are steel pipes. There are a few prestressed concrete cylinder pipes in the system. Because of the poor quality o data in the Fixed Assets file, it was not possible to precisely determine the quantity of each type of pipe in the system.

23. Not all cast iron pipe is identical. The quality of cast iron and the casting processes used have varied over time. Table 3 describes the different construction practices used over the years in New York City. As will be shown later, the increased pipe break rate with age of pipe can be attributed only in part to aging of the pipe and, to a lesser extent, the fact that newer pipe is simply stronger.

Table 3

Water Main Construction Practices in New York City

Period of Construction	Type of Pipe	Type of Joint	Strength, psi × 10^3 Bursting Tensile	Ring Modulus
Pre-1870	Horizontally cast iron pipe	Bell and spigot, with lead caulking	Unknown	
1870-1929	Vertically (pit) cast iron pipe	Bell and spigot, with lead caulking	11	31
1930-1969	Centrifugally cast iron pipe, with interior cement lining	Bell and spigot, with lead caulking	18	40
1970-1974	Ductile iron pipe, with interior cement lining	Bell and spigot, with lead caulking	42	72
1975-present	Ductile iron pipe, with interior cement lining	Push-on joint, with rubber O-ring	42	72

Pipe Break Data

24. Pipe break data were tabulated by Betz, Converse and Murdoch, Inc. (BCM), based on maintenance reports prepared by the Bureau of Water Supply for each break in a 25-year period. Breaks on hydrant laterals were not included in the computer data base, although some data on smaller pipes (<6 in.) were included. Data for 1,616 breaks between 1954 and 1978 were entered for the Bronx, while data for 2,139 breaks between 1955 and 1979 were entered for Queens.

25. The data stored in the data file included:

- a. Break report number.
- b. Break date.
- c. One or two street names, sometimes with an address.
- d. Type of break (circumferential, longitudinal, etc.).
- e. Cause of break (construction activity, corrosive environment, etc.).
- f. Size of pipe.
- g. Year pipe laid.
- h. Thickness of pipe metal at time of repair.
- i. Extent of corrosion.
- j. Structures in contact with main.
- k. Damages reported.
- l. Census block and tract for up to four blocks.

26. Since maintenance crews are more concerned with repairing breaks than with filling out break reports, a large number of the break records contained codes for "not examined," "unknown," or "blank." Another problem was the inability to pinpoint the exact location of the break from the records. When two streets were listed in the break file, it was assumed that the break occurred on the first street near or at the intersection with the second street. Other problems also existed:

- a. Pinpointing from the records the exact location of the break was often impossible.
- b. Two streets were often listed without specific reference to which one actually had the break.
- c. Street addresses and census tracts sometimes did not agree, particularly in Queens.

Nevertheless, the data were of better quality than those found in the Fixed Assets file.

27. The following sections analyze the effect of various factors on the rate of pipe breakage. To assist in comparisons, all of the break data are presented in terms of break rate in breaks per year per mile. The data in terms of number of breaks are presented in technical memorandums prepared by BCM (1981a, 1981b) for the USAED, New York.

Overall break rates

28. The overall break rate in the Bronx is 0.0746 break/year/mile while in Queens it is 0.0558 break/year/mile. Three reasons for this difference have been identified: (a) laying practices, (b) subsurface conditions, and (c) overall pipe age. These factors are discussed in more detail in the sections below.

29. The break rates in the Bronx and Queens are consistent with many other utilities reported in the literature. The rates are similar to Brooklyn, slightly higher than Staten Island, and considerably lower than Manhattan. The overall break rate in Manhattan is 0.167 break/year/mile (USAED, New York 1981). Manhattan's higher break rate results primarily from the significantly more severe loading placed on pipe in that borough due to greater traffic, more buried utilities, more subways, and the existence of a steam utility.

Type of break

30. Breaks have been classified into three types: circumferential (circular), longitudinal, and a type that includes holes whether they be blowouts or corrosion holes. This information was recorded for approximately 86 percent of the breaks in both the Bronx and Oueens. For those breaks for which the type of break was reported, some trends are clear. These data are illustrated in Tables 4 and 5 and in Figures 1-3.

31. Circumferential breaks are much more common on smaller pipes (mostly 6 and 8 in.) than on larger pipes. This is because smaller pipes are much more likely to fail as a beam.

32. The rate at which pipes experience longitudinal breaks is virtually the same for all diameters. This situation is logical since longitudinal breaks are usually due to excessive pressure which is experienced by all pipes in the system. In contrast to circumferential breaks, electrolysis holes are much more common in larger pipes. This is because larger pipes are more

Table 4

Bronx Break Rate by Type of Break and Diameter

(Breaks/year/mile and percent)

Diameter	Circular	Longitudinal	Blowout Hole	Other or Unknown	Total
10 in. and smaller	0.0853 (76)	0.0161 (13)	0.0010 (1)	0.0132 (10)	0.1256 (100)
12 in.	0.0093 (28)	0.0163 (48)	0.0021 (6)	0.0063 (18)	0.0340 (100)
14 in. and larger	0.0045 (12)	0.0145 (39)	0.0045 (12)	0.0139 (37)	0.0375 (100)
Average	0.0462 (62)	0.0159 (21)	0.0020 (3)	0.0105 (14)	0.0746 (100)

Table 5

Queens Break Rate by Type of Break and Diameter

(Breaks/year/mile and percent)

Diameter	Circular	Longitudinal	Blowout Hole	Other or Unknown	Total
10 in. and smaller	0.0568 (74)	0.0094 (12)	0.0035 (4)	0.0075 (10)	0.0772 (100)
12 in.	0.0082 (34)	0.0103 (42)	0.0023 (10)	0.0036 (14)	0.0244 (100)
14 in. and larger	0.0034 (12)	0.0046 (17)	0.0076 (28)	0.0117 (43)	0.0274 (100)
Average	0.0361 (64)	0.0089 (16)	0.0038 (7)	0.0070 (13)	0.0558 (100)

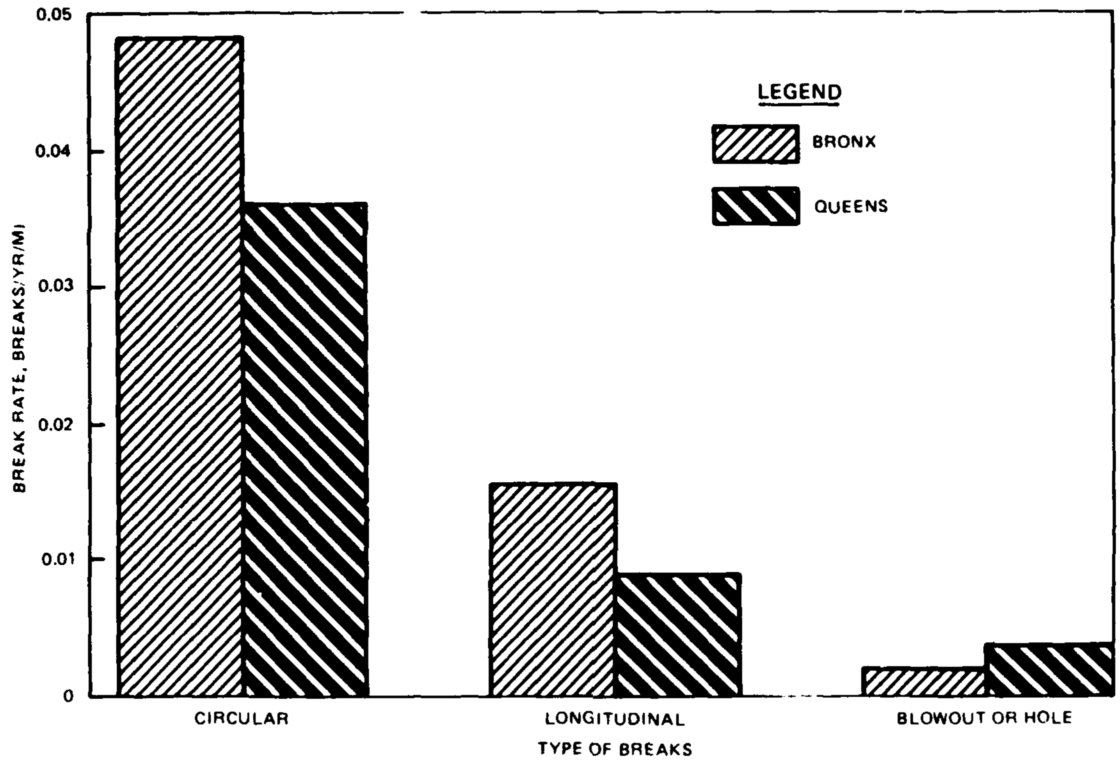


Figure 1. Break rates by type of break

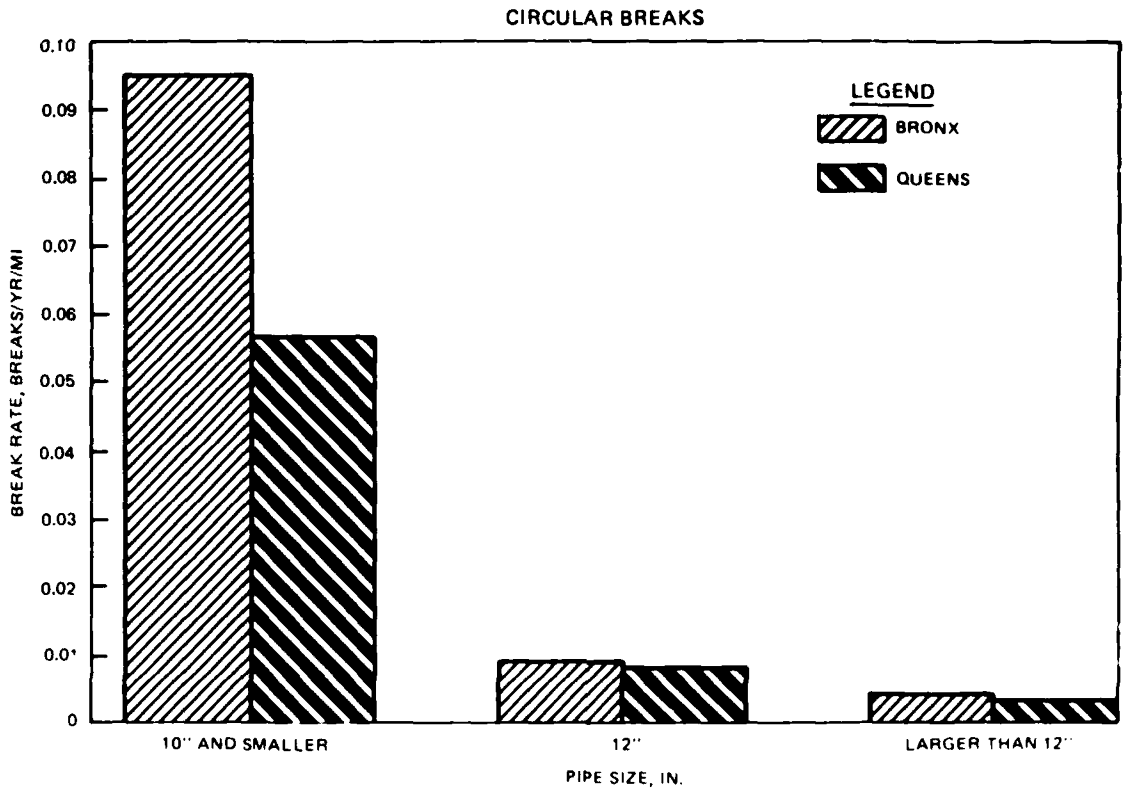


Figure 2. Distribution of circular breaks by diameter

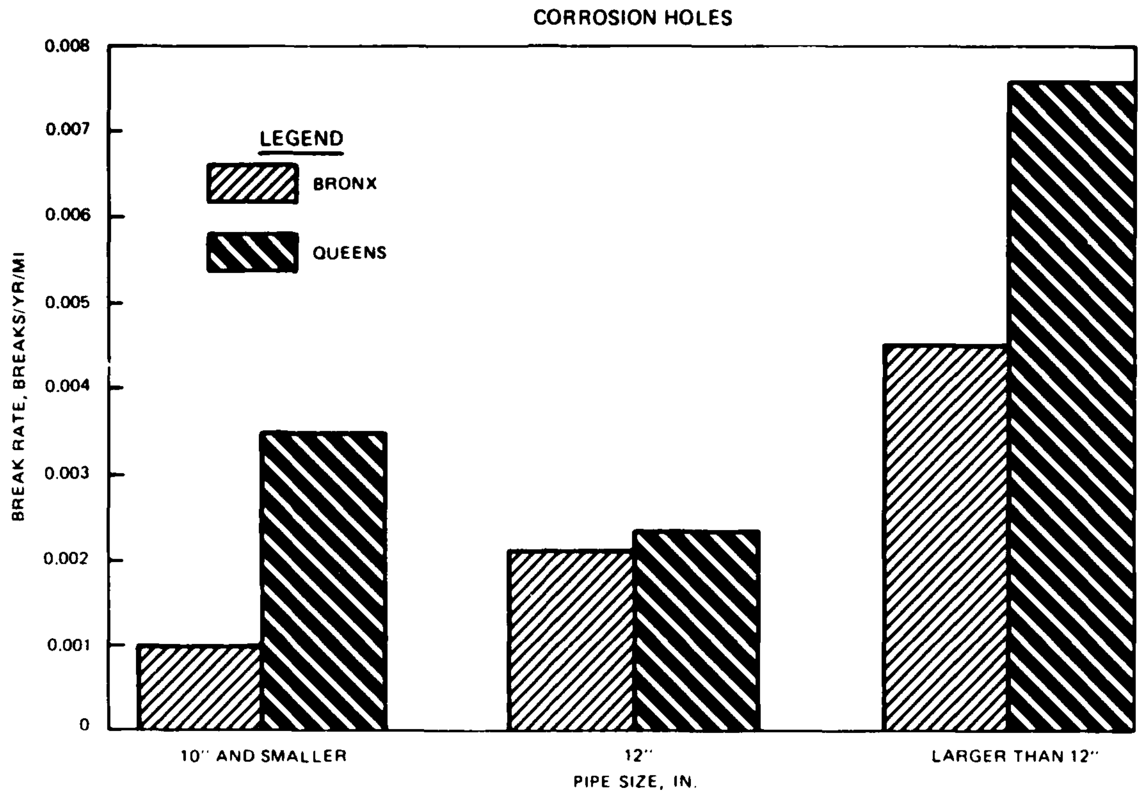


Figure 3. Distribution of corrosion holes by diameter

likely to be made out of steel, and steel pipe, with thinner walls and a generally higher susceptibility to corrosion than cast iron pipe, is much more likely to develop corrosion holes.

33. In general, the trends in the types of breaks are virtually the same in the Bronx and Queens with the exception that the overall break rate is somewhat higher in the Bronx.

Pipe diameter

34. As stated above, the pipe diameter can be an indicator of the rate of breakage. Table 6 and Figure 4 show that the break rate is especially high for 6-in. pipes, with the second highest break rate for 8-in. pipes. The break rate is roughly independent of diameter for larger pipes, except that in Queens the large number of corrosion holes in some 48- and 60-in. pipe results in higher break rates for those diameters.

35. The very high break rates for 6-in. pipes result because 6-in. pipes are not very good at supporting loads as a beam. In addition, 6-in. pipes are, on the average, older than most other diameters. For example, only 6.8 miles of 6-in. pipe have been laid in the Bronx since World War II (1945).

Table 6

Break Rates for Each Diameter

Diameter in.	Bronx breaks/year/mile	Queens breaks/year/mile
6	0.285	0.260
8	0.097	0.057
12	0.034	0.026
16	0.062	0.027
20	0.046	0.012
24	0.054	0.047
30	*	0.021
36	0.026	0.013
48	0.016	0.048
60	*	0.068
72	*	0.036

* Not enough pipe to make numerical values meaningful.

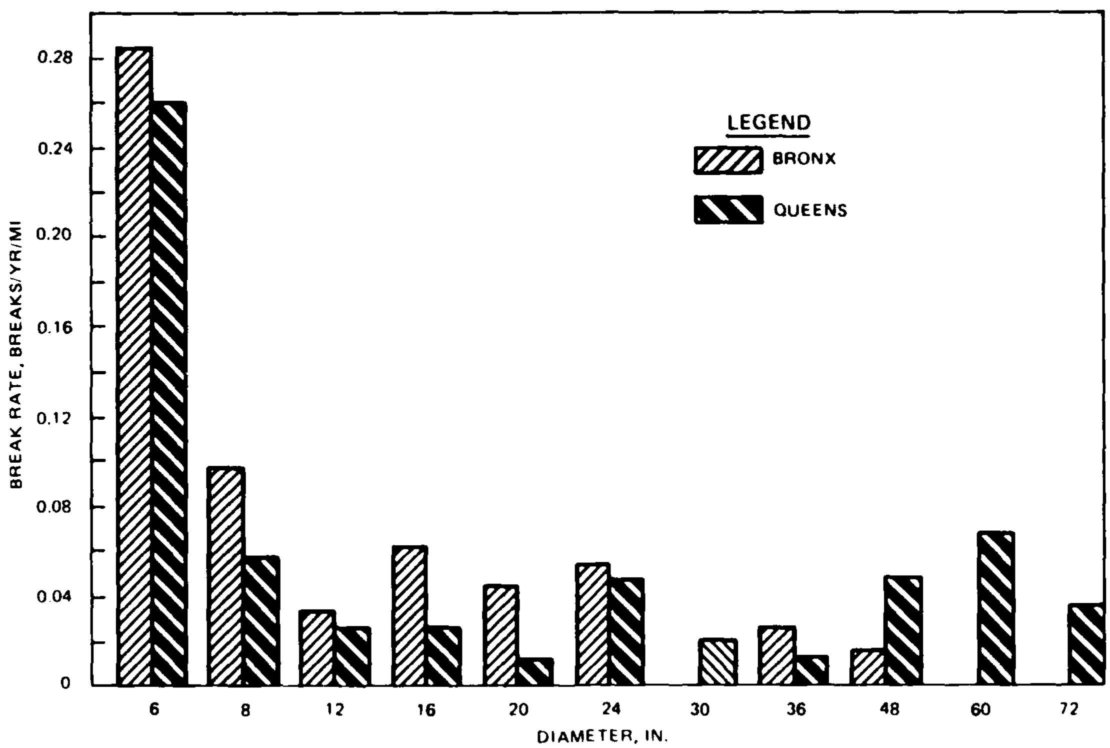


Figure 4. Break rates as a function of diameter

This is only 11 percent of all 6-in. pipe laid. By comparison, 32.3 percent of the Bronx system has been laid since 1945.

36. Table 6 provides support for the Bureau of Water Supply's policy of replacing 6-in.-diam pipes with larger pipes. The break rate of 0.285 break/year/mile is excessive even for older pipes, as will be shown later. In addition, such findings are consistent with the Manhattan and Brooklyn reports (USAED, New York 1980, 1984).

<u>Pipe thickness</u>

37. A pipe's strength is related to its wall thickness. Therefore, if a pipe's wall thickness is substantially below standard, it would be a likely candidate for failure. Unfortunately, thickness of the pipe wall was reported for only about 30 percent of the breaks. Another problem is that standard wall thickness has changed as pipe material has evolved over the years.

38. The wall thickness of the pipes for which thickness was measured was almost always acceptable. Furthermore, wall thickness standards are usually very conservative, so that even if a pipe is marginally under the standard, it is still quite strong.

39. The exception is that many of the large (>30 in.), old (pre-1900) pipes do not have a wall thickness up to standard for old pit cast iron pipe. These effects will show up more clearly in the section describing break rate and period in which pipe was laid.

<u>Contact with structures</u>

40. Contact with another structure can cause excessive load on a pipe, which can result in a break. "Contact with structures" is one of the items listed on the pipe break reports. In the Bronx, 31 percent of the break records listed contact with structures, while in Queens only 10 percent did so.

41. While the break report permitted the repair crew to identify the type of structure in contact with the main, most of the reports listed "unknown" or "other" as the types of structure. Of those reporting contact, 23 breaks in the Bronx and 3 in Queens listed contact with subways, while 27 in the Bronx and 28 in Queens listed contact with other utilities.

42. The higher number of breaks due to contact with other structures in the Bronx is fairly significant and might explain the overall higher break rate in the Bronx when compared with Queens. Consider Table 7, which illustrates that, when contact with structure breaks are eliminated from the break

Table 7

Relative Importance of Breaks Caused by Contact with Structures (Breaks/year/mile)

Types of Breaks	Bronx	Queens
All breaks	0.0746	0.0558
Contact with structures	0.0232	0.0057
Other breaks	0.0514	0.0501

data set, the break rates in the Bronx and Queens are similar. This means that, traditionally, pipe laying and construction practice in the Bronx has been responsible for a large number of breaks (approximately 31 percent in the Bronx versus 10 percent in Queens). One reason is that the subway system is more extensive in the Bronx than Queens. Another is that the population and activity are simply more concentrated in the Bronx.

43. An alternative reason for the higher break rate in the Bronx is that there is more "ledge rock" near the surface in the Bronx. The difficulty of excavation associated with the rock makes it more likely that pipe in the Bronx would be poorly bedded. Leak detection surveys have found a large number of leaks caused by poor bedding in the Bronx.

Cause of break

44. Another type of data recorded on the break report is the "cause of the break." This refers to the repair crew's opinion of the cause of the break. This information would have been useful if it had been filled in consistently. However, for both the Bronx and Queens, the response given 78 percent of the time was "unknown."

45. For those breaks for which a cause was given, construction activity was by far the most common cause in the Bronx, accounting for roughly 17 percent of the breaks. This is somewhat consistent with the data presented in the section on "contact with structures," which show that 31 percent of the breaks in the Bronx cited "contact with structures." There is considerable inconsistency in filling out the break reports in that "interference with

utilities" is noted for 14 breaks in the Bronx under "cause of break," yet 27 breaks in the Bronx are listed as having "contact with utilities."

46. In Queens, "construction activity" is listed as the most common cause of breaks (7 percent), but "corrosive environment" is a close second (6 percent). Corrosion-related breaks were not evenly spread throughout Queens but were concentrated in a few large steel mains with a sprinkling of breaks through the remainder of the borough.

47. "Improper installation" was cited in 51 breaks in Queens versus a mere 5 in the Bronx. Surprisingly, however, these breaks were not clustered along any individual pipe but were spread fairly randomly through Queens. The only exception was some 8-in. pipe along 86th Ave. between 248th and 253rd Sts. laid in 1936.

48. Another entry on the break report consisted of an evaluation of whether corrosion or tuberculation was identified at the break site. Unfortunately, approximately half of the Bronx break reports and 70 percent of the Queens break records reported "unknown" for this entry. Virtually all old pipes will have some corrosion. Without a more detailed analysis of the extent of the corrosion and its relationship to the break, the information on corrosion contained in the break report is not very useful.

Weather

49. Break rates tend to increase during periods of cold weather. Such increases are generally felt to be due to the extra loading on the pipe due to frost penetration. However, the higher break rate may also be influenced by thermal contraction due to a decrease in water temperature.

50. In the Bronx and Queens, break rates were much higher in the winter months, as shown in Figure 5. The seasonal trends existed for all diameters, although the effects were more pronounced for smaller pipes.

51. While the Bureau of Water Supply can choose to lay new mains deeper, little can be done to prevent this higher break rate during the winter for in-place pipes. The Bureau of Water Supply can, however, schedule more routine maintenance during warmer weather to leave repair crews with more time to repair breaks during the winter.

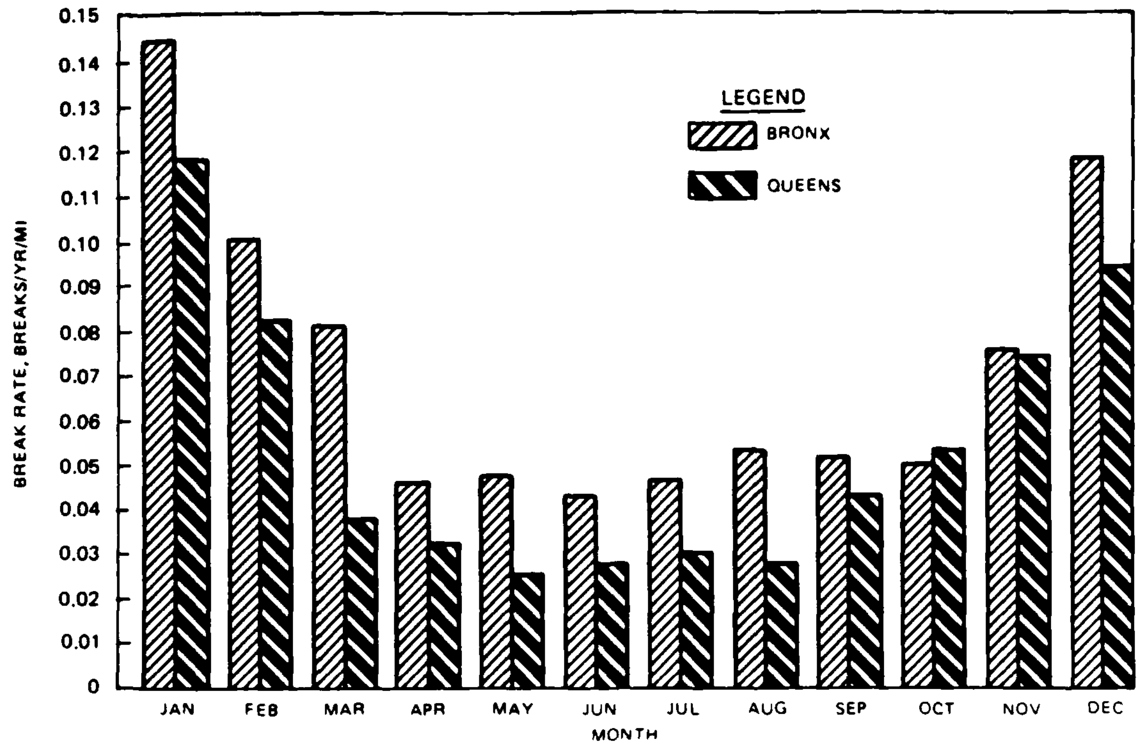


Figure 5. Break rate as a function of month

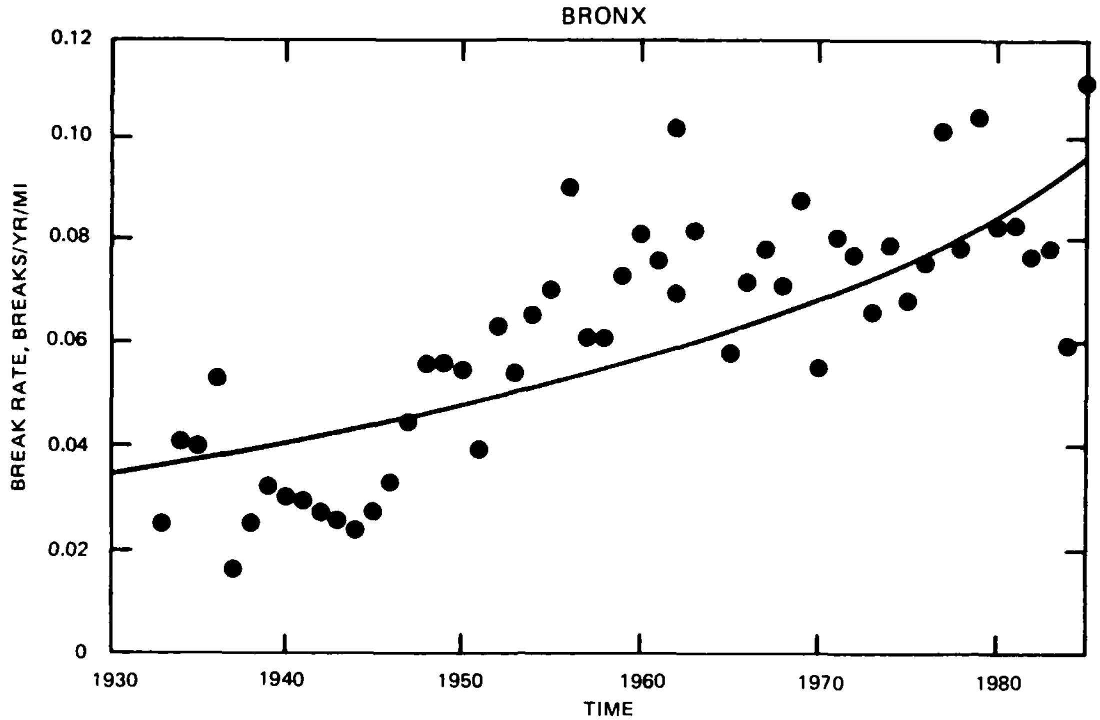
Trends in Break Rate

52. It was mentioned earlier that older pipe tended to have higher break rates than newer pipe. This is partly due to deterioration of the pipes with time and partly due to improved materials and construction. This section will show the relative impact of each of those effects. In addition, an overall rate of increase in breakage will be determined. This information is a key input into the economic evaluation presented later.

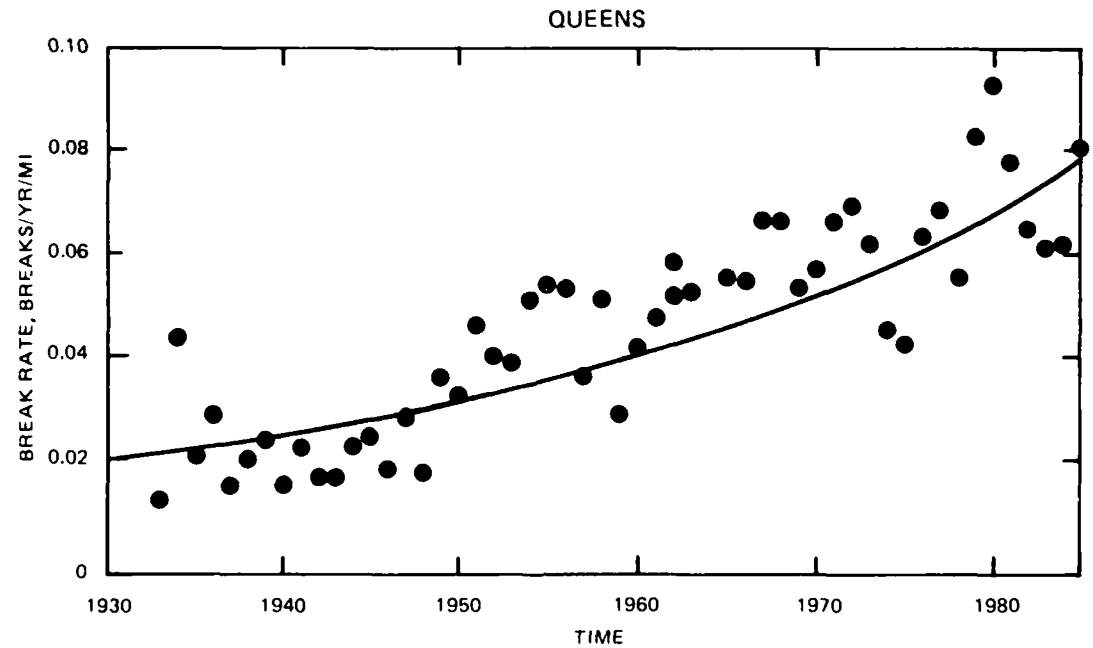
53. First, the overall trends in break rate versus time are described. Then the effect of the period in which the pipe was laid is investigated. Finally, the relative effects of period laid and age are analyzed to arrive at a rate of increase of breakage due to deterioration.

Historical break rate

54. The history of break rates since 1933 is summarized in Figures 6a and 6b for the Bronx and Queens, respectively. The figures are based on break rates calculated by the Bureau of Water Supply and are not taken from the break record data base described earlier.



a. The Bronx



b. Queens

Figure 6. Break rate versus time

55. The figures clearly show that break rates are increasing. The data best fit the equation

$$J = a \exp [b^* (t - 1933)] \qquad (1)$$

where

J = break rate in year t , breaks/year/mile

a = regression coefficient, breaks/year/mile

b* = rate of increase of breakage, 1/year

t = year

56. Equation 1 is consistent with equations presented by Shamir and Howard (1979) and Walski and Pelliccia (1982). It is, however, only slightly better than a linear equation, relating break rate and time. The parameter b^* is of special concern in the above equation since it is approximately equal to the annual increase in break rate. For example, if $b^* = 0.02$, the break rate is increasing at a rate of 2 percent per year. The parameter b^* accounts for the fact that: (a) the pipes are deteriorating due to aging, (b) the overall age of pipes in the system is increasing, and (c) fabricated and construction practices have differed over time. For the economic evaluation presented later, it will be necessary to separate the fact that the average age of pipe is increasing and to merely account for the gradual deterioration of pipe. This parameter will be called b^* and is determined below.

57. The rate constants a and b^* for the Bronx and Queens are given below:

Coefficient	Bronx	Queens
a	0.0360	0.0221
b*	0.0185	0.0241

58. The coefficients given above indicate that the break rate has been higher in the Bronx but is increasing at a higher rate in Queens. If these trends continue, the break rate in Queens will exceed the Bronx break rate in the year 2020. These trends should not be too surprising since more breaks in the Bronx are due to poor bedding and contact with structures. This type of break does not generally get worse with time. Corrosion tends to be more important in Queens. Problems due to corrosion will get worse over time. The

differences in rates are only slight since breaks due to all sorts of causes have occurred in both boroughs.

59. It is possible to use a linear function instead of the exponential function given in Equation 1. The goodness-of-fit for a linear function is almost as good as that of the exponential. However, since present worth calculations involve exponential functions, the mathematics of exponential functions of break rate versus time makes use of the exponential function more desirable.

Period laid

60. Pipes laid many years ago are expected to have higher break rates than those laid in recent years for two reasons. First, construction practices and pipe materials have generally improved over time (with some exceptions); second, corrosion tends to weaken pipe over time. The aging effect will be examined later. This section presents data to illustrate that pipes that were laid many years ago break at higher rates than those laid recently, regardless of the reason for the breaks.

61. Table 8 and Figure 7 illustrate the change in break rates over time. (Approximately 28 percent of the break records in Queens and 7 percent in the Bronx did not have the year the pipe was installed listed on the break record.)

62. After some very high break rates for pipes laid in the late 1800's, pipes laid in the Bronx until World War I show a low break rate. After the late 1920's, the break rate again becomes low and continues to decrease for pipes laid until the present day.

63. The data from Queens are a bit more difficult to interpret. First, data on the year in which a pipe was laid are inconsistent for pipes laid before 1915, so all pipes laid before 1915 are grouped together. The high number of pipes labeled in the Fixed Assets Inventory as being laid in the early 1910's tends to obscure the suspected high break rate of pipes laid before 1900. Another anomaly is that Queens purchased some bad batches of pipe from the late 1950's through the late 1960's. This resulted in unusually high break rates for pipes laid during those years.

64. Both boroughs exhibited very low break rates in pipes laid since 1970. This is apparently due to good performance of ductile iron pipe, at least while it is new. The Bureau of Water Supply is currently using Class 56 ductile iron pipe for 8- and 12-in. mains, class 54 for 20-in. mains, and

Table 8

Break Rates by Pentad Laid (breaks/year/mile

Pentad	Bronx	Queens
1875-1879	0.210	
1880-1884	0.437	
1885-1889	0.163	
1890-1894	0.184	
1895-1899	0.186	
1900-1904	0.104	
1905-1909	0.076	
1910-1914	0.050	0.015*
1915-1919	0.098	0.089
1920-1924	0.108	0.044
1925-1929	0.104	0.064
1930-1934	0.053	0.058
1935-1939	0.046	0.080
1940-1944	0.062	0.038
1945-1949	0.078	0.041
1950-1954	0.051	0.031
1955-1959	0.066	0.050
1960-1964	0.056	0.103
1965-1969	0.034	0.080
1970-1974	0.008	0.013
1975-1979	0.018	0.012
Average	0.0746	0.0558

* Pre-1915.

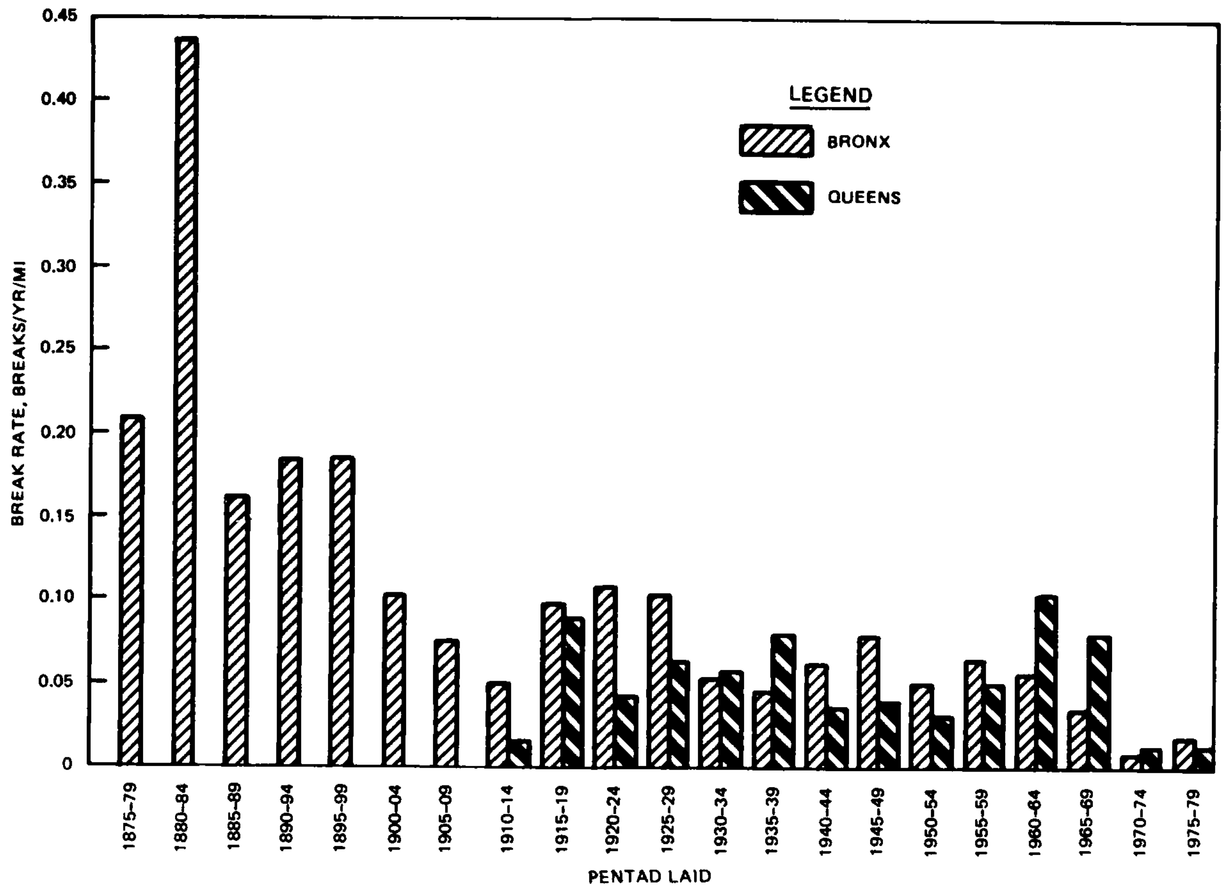


Figure 7. Break rate as a function of pentad laid

Class 53 for larger diameters. This is a relatively thick-walled pipe compared with what is used by other water utilities. The Bureau of Water Supply considers such pipe necessary because of the severe loads placed on pipe in New York City and thicker walled pipe can be direct tapped more easily.

Overall rate of aging

65. One would expect the break rate to increase with the age of pipes. For each break in the data base, the age of the pipe when the break occurred was determined, and a regression analysis was performed between the age of the pipe and the break rate for a given age. The data fit the same exponential function as the plot of break rate versus time given earlier. That is

$$J = a \exp (b't) \tag{2}$$

where

J = break rate, breaks/year/mile

a = regression coefficient, breaks/year/mile

b' = rate of increase of breakage with age, 1/year

t = age of pipe, year

66. The coefficients of the above equation for the Bronx and Queens are given below:

Coefficient	Bronx	Queens
a	0.0327	0.0312
b'	0.0203	0.0104

67. The above tabulation shows that the break rate does increase with the age of the pipe. The rate of increase is slightly lower in Queens than the Bronx because, as mentioned earlier, Queens experienced some problems with new pipe. Much of this pipe was replaced before it had time to "age."

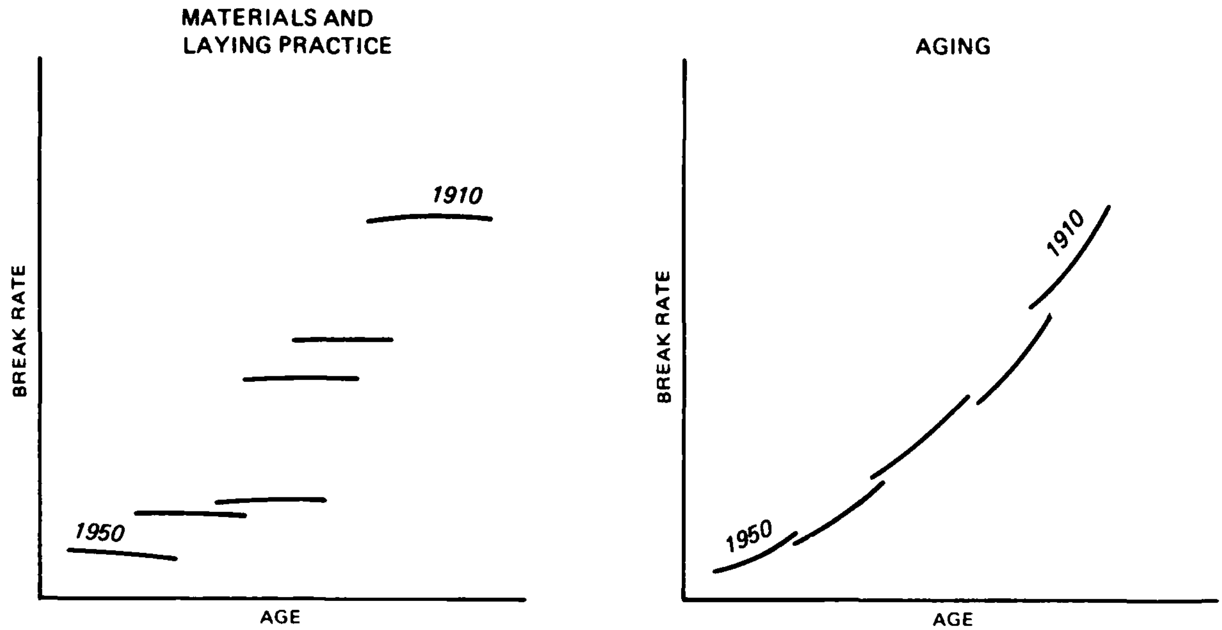
68. The above rates of aging do not distinguish between deterioration of pipe and the fact that materials and laying conditions have changed with time.

Aging rate for individual pipes

69. The values of b' presented earlier are an overall rate of aging of the system. For an economic analysis, it is necessary to separate the fact that pipe materials and laying practices have changed with time from the fact that pipes are deteriorating with age. To do this, pipes were grouped according to the 5-year period (pentad) in which they were laid. The break rate for each group of pipes was followed through the 25-year period covered by the break rate data base. This procedure could be used to determine the rate of aging of pipes because all pipes in a group: (a) are of roughly the same material and laying methods, and (b) have been in the ground the same period of time.

70. If pipes do not deteriorate with age, the break rate should remain constant over the 25-year period for which data are available. The data would look like the hypothetical graph shown in Figure 8a. In this case, pipe material and laying practice would account for the apparent difference in break rate with age.

71. On the other hand, if deterioration due to age were the only factor explaining the increasing break rate with time, the data would look like



a. Materials and laying practice

b. Aging

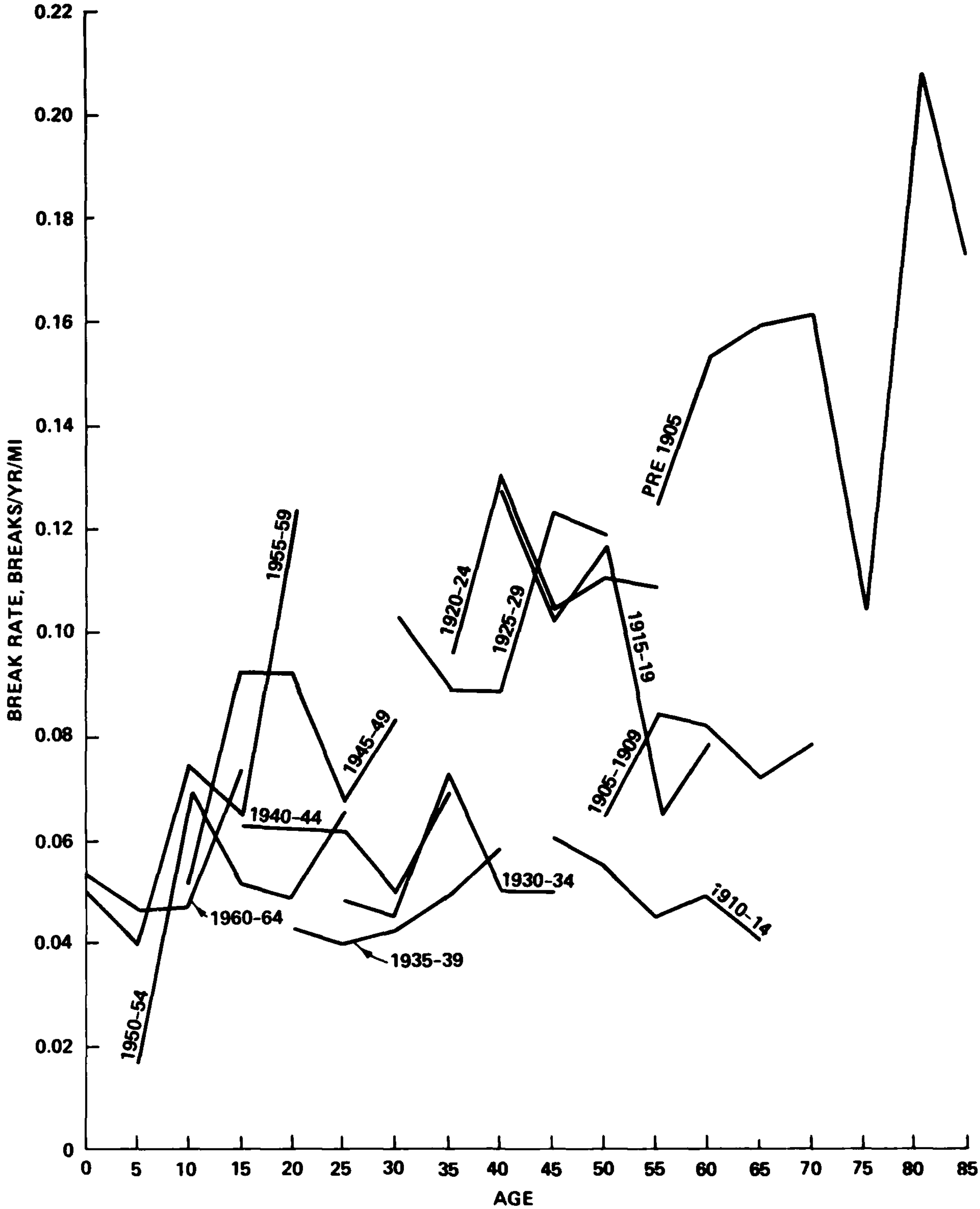
Figure 8. Examples of possible relationships between pipe age and break rate

Figure 8b. When a pipe is a certain age, it would have the same break rate regardless of the year in which it was laid.

72. In reality, the break rates fall somewhere between the two extremes shown in Figure 8. The actual data for the Bronx and Queens are shown in Figure 9. Variation in the break rate from one pentad to the next is fairly significant due, as one would expect, to the effects of weather and other random causes. To smooth the data, a straight line was fit to the break rate data for every group of pipes using regression analysis. These lines are plotted in Figure 10.

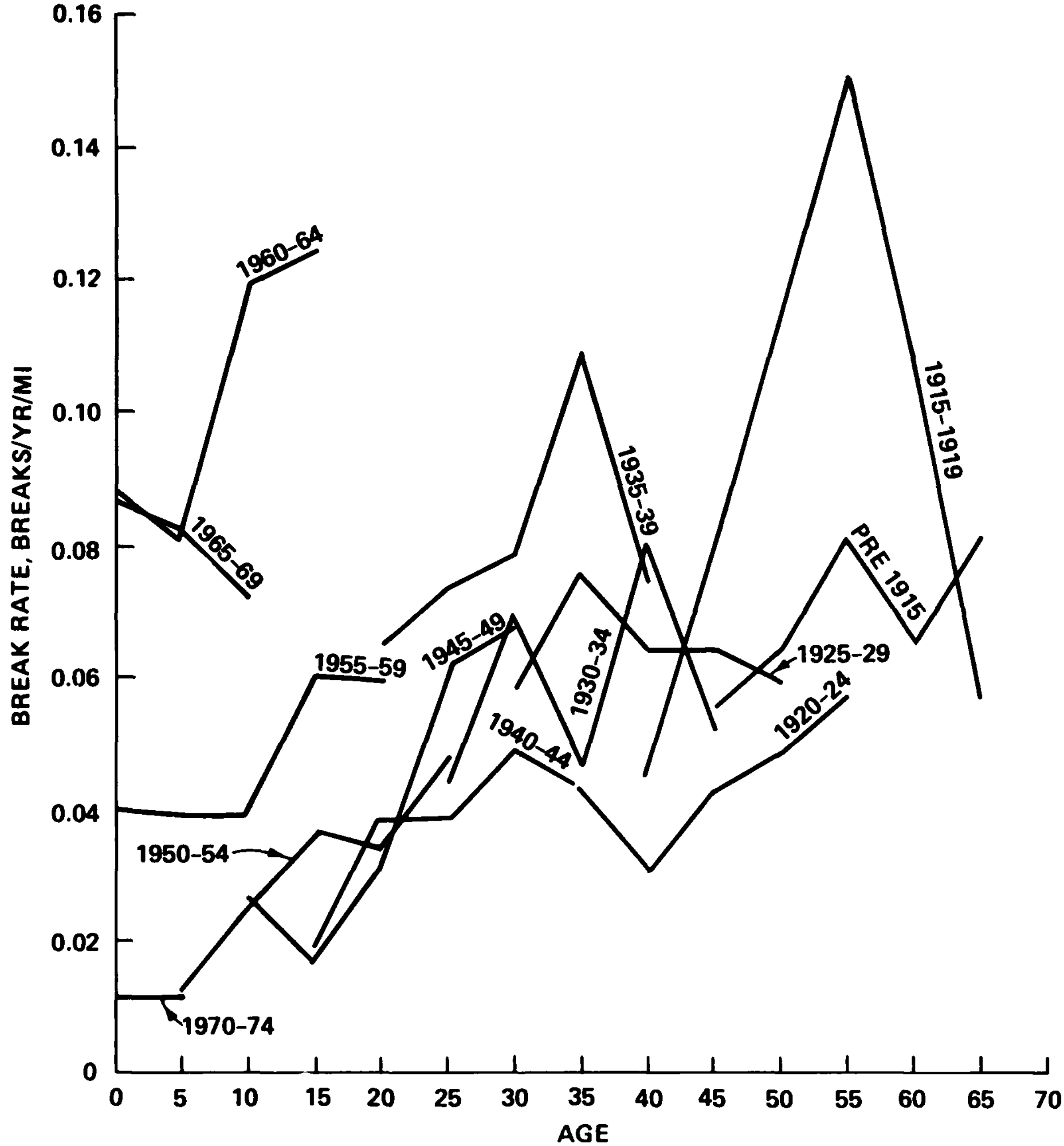
73. The break rates given for pipes laid in Queens for the pre-1915 period are too high because the mileage of pipes laid in those years has apparently been overestimated, as discussed earlier. With more reasonable estimates of mileage laid, the break rates in that pentad would be consistent with other pentads. Unfortunately, there is no way to determine the correct value.

74. While a few of the lines in Figure 10a show a slight downward slope, the data for the Bronx show that the break rates for pipes are increasing as a function of age of the pipe. The lines all lie roughly in the same



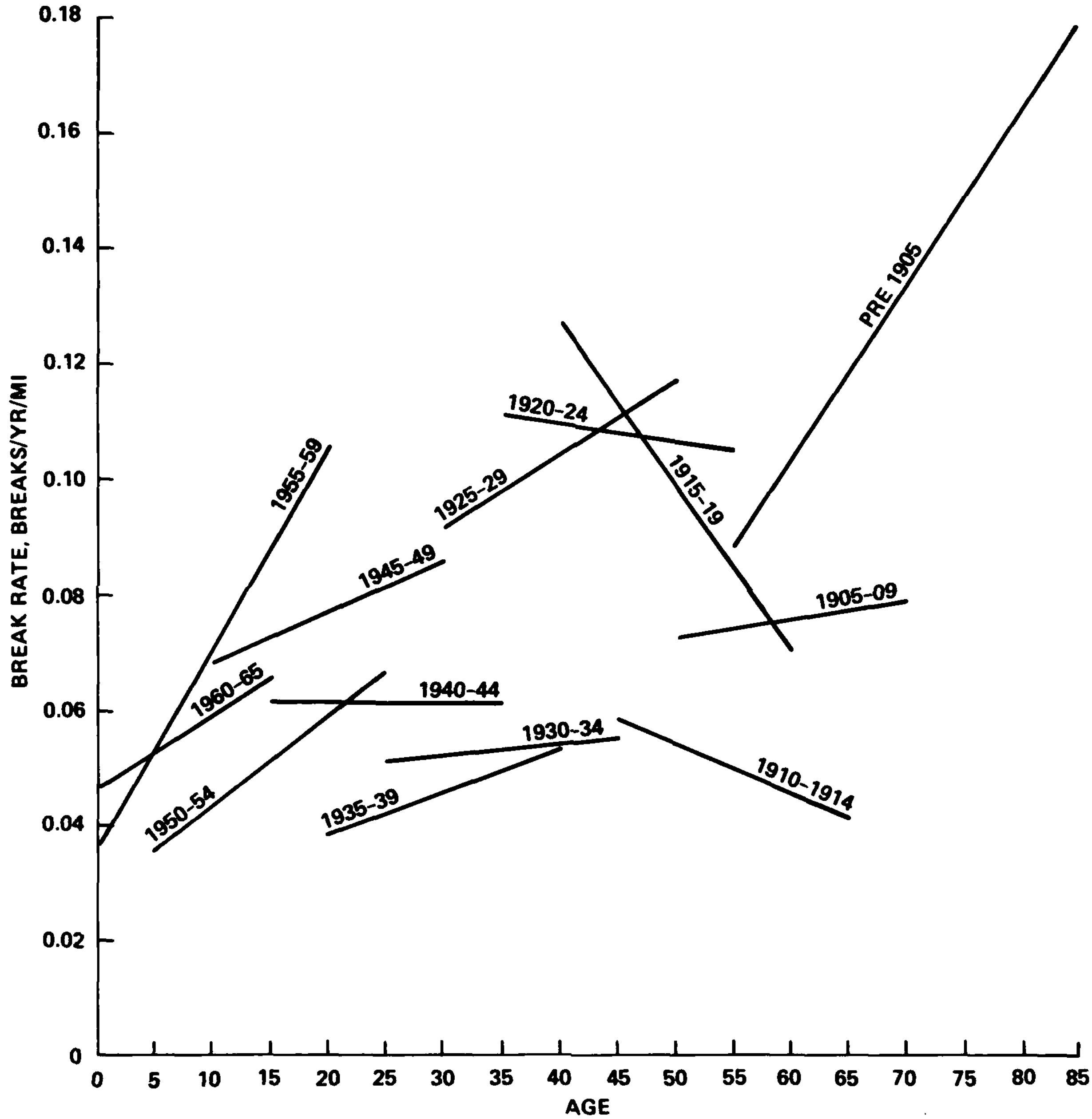
a. The Bronx

Figure 9. Break rate versus age for pipes laid in pentad indicated (Continued)



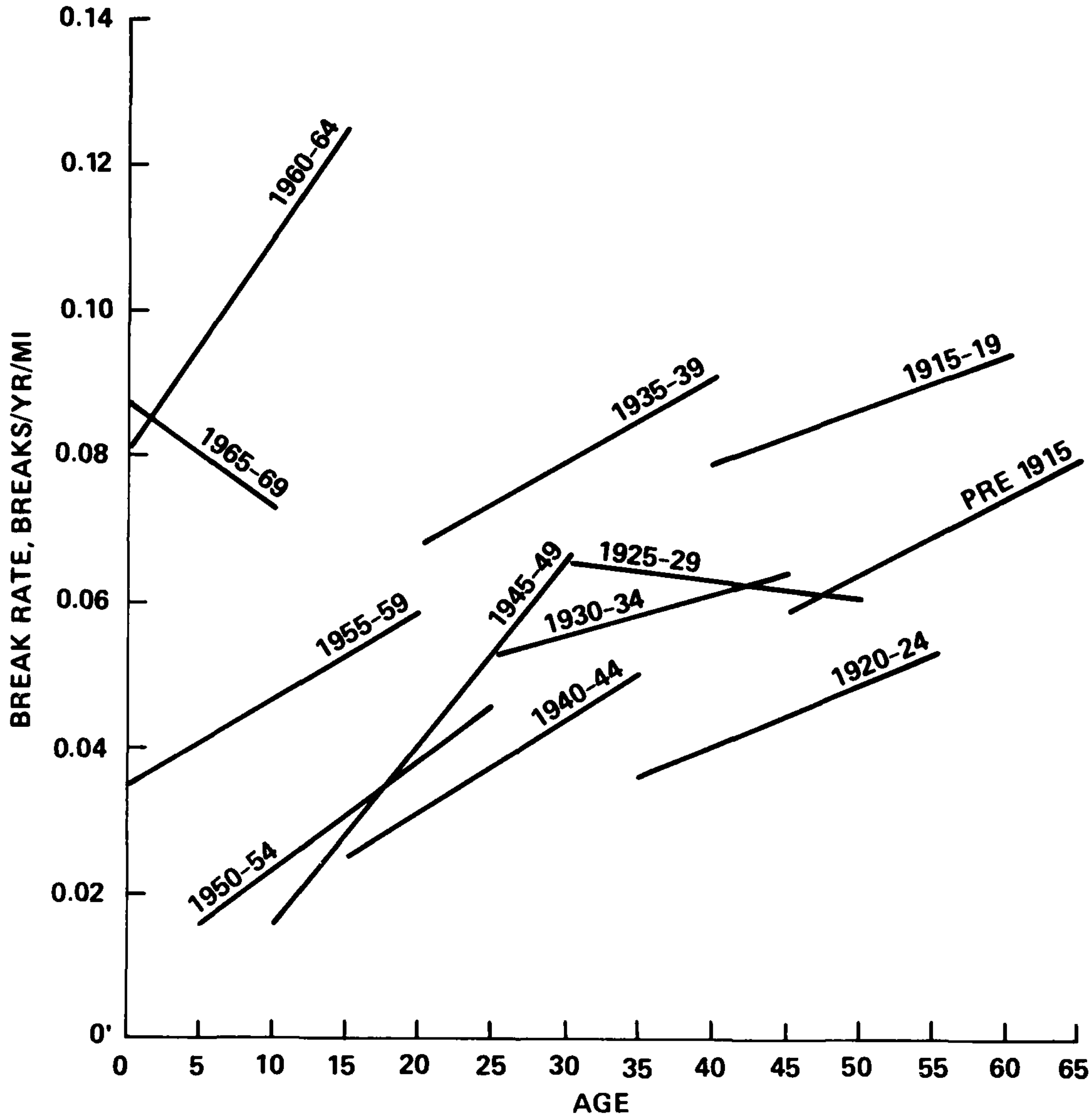
b. Queens

Figure 9. (Concluded)



a. The Bronx

Figure 10. Smoothed break rate versus age
(Continued)



b. Queens

Figure 10. (Concluded)

band, which indicates that deterioration due to age is a more significant factor than period laid in explaining the increase in break rate with age. The average annual rate of increase of break rate is 1.8 percent, which is slightly less than the overall increase in the rate of breakage with time (2.0 percent).

75. The data for Queens are somewhat different in that for two pentads (1960-1964 and 1965-1969) the break rates were significantly higher than for others. This anomaly was apparently due to the use of several bad batches of pipe. This pipe was purchased from a foundry that had operating problems, which resulted in brittle pipe. In these years, the pipe materials had a greater influence on the break rate than deterioration due to age. When data for this decade were eliminated from the calculations, the overall annual increase in break rate due to deterioration was 2.5 percent. The 2.5 value for increase in break rate due to deterioration is actually higher than the annual increase in break rate of 1.0 percent (b') presented above. This number (2.5) is a better indicator of the rate of increase of breakage due to deterioration, which is important in subsequent economic analyses and does not include the effect of the bad batches mentioned earlier.

Summary

76. The analysis of pipe break data has shown that:

a. Smaller pipes tend to break at a higher rate than larger pipes.

b. Smaller pipes tend to have circumferential breaks, while larger pipes tend to have more blowout holes.

c. The higher break rate in the Bronx when compared with Queens can probably be explained by the higher degree of congestion of structures and different subsurface conditions in the Bronx.

d. Pipes tend to be more likely to break in cold weather.

e. Pipe break rates have increased at approximately 2 percent per year.

f. The increase in break rates appears to be due more to pipe deterioration with age than with different laying practices.

PART III: ECONOMIC EVALUATION OF PIPE REPLACEMENT

77. This part presents listings of pipes in the Bronx and Queens that need to be replaced and discusses the rationale used. First, a projection of trends in pipe break costs into the future is given. Replacement rules and their implications are then discussed, and critical pipe break rates are determined. Finally, the listings are presented.

Pipe Replacement Cost Trends

78. As was shown earlier, the break rate for pipes is increasing with time. These trends should continue and, assuming no massive pipe replacement projects will be undertaken, it is possible to use Equation 1 to predict the number of breaks that are likely to occur in the future. Pipes of all sizes will break, and the costs associated with a break will depend on diameter and site conditions. However, using a weighted average break cost of $8,600 per break as described in Appendix A for direct costs to the Bureau of Water Supply, it is possible to estimate the expenditures for break repair for various years (neglecting inflation). These values are given in Table 9 and are based on the mileage of pipe actually in place in 1985. The number of breaks and repair costs would actually be higher since additional miles of pipe are likely to be laid. The important point illustrated in Table 9 is not so much

Table 9

Projections of Number of Breaks and Direct Repair Costs in the Bronx and Queens

	Number of Breaks		Annual Cost for Repair, $K*	
Year	Bronx	Queens	Bronx	Queens
1985	82	118	705	1,015
1990	89	134	763	1,152
1995	98	151	843	1,299
2000	108	170	929	1,462
2010	129	216	1,109	1,858
2020	156	275	1,342	2,365

* Not including inflation.

the expenditure estimates but, more so, the fact that expenditures are increasing significantly with time, and in fact will roughly double over the next 50 years. This growth can be slowed if the weakest pipes in the system are replaced. Those pipe sections are identified in a later section.

79. With the ever-increasing break rate, more pipes will become candidates for replacement as time passes. Since the new pipes being laid are fairly heavy-walled ductile iron, it is felt that the new pipes should have a better record with respect to pipe breakage than existing pipes. Even with the improved pipe, the Bureau of Water Supply can expect to spend increasing sums of money maintaining its water system each year. As the system is gradually replaced with new pipes over time, the growth rate will decrease and the break rate may eventually level off at a rate somewhat greater than the 1985 rate.

80. Since they only include direct costs to the Bureau of Water Supply, the costs presented in Table 9 are a lower bound on the real costs of a pipe break. There is a large indirect cost associated with each pipe break. The magnitude depends on the size, location, time of day, and season of the break. In a well-drained, fairly rural area, such costs are minimal. However, in a congested area with other underground utilities and heavy traffic, the indirect costs borne by others can be in the millions of dollars. These costs would include traffic delays, deterioration of pavement, loss of business due to water damage and repair work, damage to other underground utilities, and short-term degradation of water service and fire protection. The exact values of these indirect costs for each pipe are difficult to quantify but should be included in any economic evaluation.

Pipe Replacement Rules

81. Overall maintenance and replacement costs can be minimized by identifying bad pipes that can be replaced at a lower cost than what would result if they were allowed to break and be repaired. An economic replacement rule and relevant cost data for use with the rule are derived in Appendix A and can be summarized as: Replace the pipe T years in the future, where

$$T = \frac{1}{b} \log \left(\frac{r \text{ Repl}}{\text{TotO\&M}} \right) \tag{3}$$

where

T = number of years in future to replace pipe, year

b = rate of increase of pipe breaks, 1/year

r = interest rate, fraction

Repl = replacement cost for pipe, \$/mile

TotO&M = total annual operation and maintenance (O&M) cost of existing pipe above that of new pipe, \$/mile/year

82. The above rule gives some general guidance on when a pipe segment should be replaced. In general, a pipe should be replaced in the near future if the O&M cost is relatively high with respect to the annualized replacement cost and the rate of increase in pipe breaks is high.

83. For the purpose of this report, it is necessary to identify a critical pipe break rate J^* . If a pipe breaks at a higher rate, it is economical to replace it rather than to continue to repair the pipe. The critical break rate depends on a variety of parameters as described in Appendix A. However, for the purpose of identifying poor sections of pipe, it is possible to use average values for such items as leakage rate and leak detection costs to arrive at a replacement rule. Using Equation A13 and cost data from Appendix A, the following critical break rate can be developed for the Bronx and Queens:

$$J^* = \frac{(216\ C_r - 5{,}4000)}{C_b} \tag{4}$$

where

J^* = critical break rate, breaks/year/mile

C_r = unit price for pipe replacement, \$/ft

C_b = cost of a pipe break, \$

The cost of a break and the cost of pipe replacement are a function of many factors, most importantly, the diameter of the pipe. The critical break rates listed in Table 10 therefore depend on the pipe diameter. As mentioned above, there are indirect costs associated with breaks that cannot be quantified. To bound the impact of these indirect costs on critical break rate, a low value

Table 10

Critical Break Rates for Pipes (breaks/year/mile)

Diameter in.	Low Indirect Costs	High Indirect Costs
8	1.23	0.27
12	1.17	0.31
20	1.61	0.47
36	5.49	1.98
48	9.31	3.36
60	14.1	5.09

of zero and a high value of $40,000/break will be used. The high value for indirect cost is meant to represent a worst case for routine breaks, although, in some special instances, much higher costs have been encountered. Table 10 shows that smaller pipes should be replaced at lower break rates than larger pipes. This is because the cost of a break increases fairly slowly with diameter while the cost of a replacement pipe increases much more dramatically with diameter. Replacement criteria for 6-in. and smaller diameter pipes are discussed in a later section.

84. Table 10 can be used by calculating the break rate of a pipe or group of pipes. If the break rate is higher than the value given in the column labeled "Low Indirect Costs," it should be replaced. If it is lower than the value in the column labeled "High Indirect Costs," it should be left in the ground. If it falls between the two values, the decision needs to be based on a closer investigation of site-specific conditions. There will be special cases in which the cost of a break or the cost of replacement are very different from the values used in deriving Equation 4. In those cases, a formula like Equation 4, but with different coefficients, can be developed using the procedure given in Appendix A.

85. The rule of thumb that has been used by the Bureau of Water Supply to identify pipes needing replacement is "two breaks per block." This rule does not specify a time period during which those two breaks might occur. In order to compare it with the critical break rates in Table 10, assume that those two breaks occur within a 20-year period and that an average block

length is 400 ft. With these conditions, the "two breaks per block" rule corresponds to a critical break rate of 1.3 breaks/year/mile, which falls within the range of critical break rates listed in Table 10.

Identifying Pipes to be Replaced

86. Once the critical break rates are known, it is necessary to compare the actual break rates of pipes with the critical break rate for that size pipe to determine if the pipe should be replaced. Because of economies of scale in laying pipe, utilities would rather replace pipes in fairly large areas rather than randomly replacing pipe one city block at a time. Therefore, pipes in the Bronx and Queens were grouped into "projects" for which the actual break rates were calculated. Projects consist of one to several contiguous city blocks, each having at least one pipe break. Pipes within a given project would have the same or similar diameters. For example, if 12-in. and 48-in. pipes were in the same street, they would not be considered as the same project since each pipe's critical break rates are so different.

87. For each possible project, several parameters, including the length, diameter(s), number of breaks, and length of time over which the breaks were observed, were recorded from maps and computer files. For most pipes, the length of observation was 25 years since they were in place at the beginning of the time covered by the pipe break inventory. For pipes that were installed during the period of record covered by the break inventory, the value is less than 25 years. The actual break rate for the project was then calculated from the definition of break rate as

$$J = \frac{(NB)\ 5{,}280}{(LP)(TP)} \qquad (5)$$

where

NB = number of breaks in time period of record

LP = length of pipe in project, ft

TP = time period, years

88. Once the actual break rates were determined, they were ranked for the Bronx (Table 11) and Queens (Table 12). The tables are divided into two parts depending on whether the project is economically justifiable without

Table 11

Pipes Requiring Replacement in the Bronx

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate*
Pipes Needing Replacement					
Young Ave near Mace Ave	25	4	8	400	2.11
Tenbroeck Ave near Burke Ave	25	4	8	400	2.11
E135th St between 3rd Ave and Lincoln Ave	25	4	12	500	1.69
E138th St Near Willis Ave	25	3	12	400	1.58
Split Rock Ave below City Line	25	3	12	400	1.58
W235th St between Oxford Ave and Johnson Ave	25	3	8	400	1.58
Legget Ave from Bruckner Blvd to Garrison Ave, and Bruckner Blvd from Legget Ave to Timpson Pl	25	7	8-12	950	1.56
Story Ave from Rosedale to Theriot Ave, and Taylor Ave from Bruckner Blvd to Story Ave	18	15	8-12	2,900	1.52
Lafayette Ave between Zerega Ave and Brush Ave	25	4	8	600	1.41
Story Ave near Morrison Ave	25	4	8	600	1.41
E166th St between Clay Ave and Brook Ave	25	3	12	500	1.27
Pipes Probably Needing Replacement					
Adee Ave between Throop Ave and Young Ave	25	8	8	1,400	1.21
Barreto St between East Bay Ave and Viele Ave	25	5	8	1,000	1.10
Pugsley Ave between Chatterton Ave and Powell Ave	25	8	8	1,600	1.06

(Continued)

* Breaks per year per mile.

(Sheet 1 of 3)

Table 11 (Continued)

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate
Pipes Probably Needing Replacement (Cont.)					
Fteley Ave between E172nd and E174th Sts	25	6	8	1,200	1.06
195th St between Clafin Ave and Reservoir Ave	25	3	8	700	0.91
Watson Ave between Croes Ave and Rosedale Ave	25	5	8	1,200	0.88
Westervelt Ave between Astor Ave and Pelham Parkway	25	3	8	800	0.79
Bronx Blvd between E221st and E223rd Sts	25	3	12	800	0.79
Schieffelin Ave between E225th and E224th Sts	25	3	8	800	0.79
Harding Ave between Reynolds Ave and Longstreet Ave	25	3	8	800	0.79
Seward Ave between Zerega Ave and Havemeyer Ave	25	4	8	1,100	0.77
Dereimer Ave between Nereid Ave and Pitman Ave	25	5	8	1,400	0.75
Grandview Place between E167th St and E168th St, and Grand Concourse between McClellan St and E Clark Pl	25	10	8-12	2,900	0.73
White Plains Rd between E215th and E217th Sts	25	3	12	900	0.70
Balcom Ave between Waterbury Ave and Harrington Ave	25	4	8	1,200	0.70
St. Lawrence Ave between Seward Ave and Randal Ave	25	3	8	900	0.70
Laconia Ave between Burke Ave and E211st St	25	7	8-12	2,100	0.70
E233rd St between Provost Ave and Boston Rd	25	5	12	1,600	0.66
Grand Concourse between Kingsbridge Rd and E196th St	25	3	20	1,000	0.63

(Continued)

(Sheet 2 of 3)

Table 11 (Concluded)

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate
Pipes Probably Needing Replacement (Cont.)					
McOwen St between Boston Rd and Eastchester Pl	15	3	8	1,700	0.62
Cannon Pl between W238th St and Giles Pl	25	4	8	1,400	0.60
Lafayette Ave between Colgate Ave and Boynton Ave	25	4	12	1,400	0.60
Seymour Ave between Arnow Ave and Mace Ave	25	6	8	2,300	0.55
Riverdale Ave between W231st and W234th Sts	25	4	8	1,600	0.53
Conner St between Clementine St and Hollers Ave	25	3	12	1,300	0.49
Bullard Ave between E239th and E237th Sts	25	4	8	1,800	0.47
E167th St between Sherman Ave and Morris Ave, and Grant Ave between E167th St and McClellan St	25	3	12	1,400	0.45
Boston Ave between E176th and E173rd Sts	25	5	12	2,400	0.44
Spencer Ave between W260th and W262nd St	25	3	8	1,600	0.40
Bathgate Ave between E179th and E182nd Sts	25	4	8	2,200	0.38

(Sheet 3 of 3)

Table 12

Pipes Requiring Replacement in Queens

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate*
Pipes Needing Replacement					
160th Ave between 90th and 91st Sts, and 91st Ave between 163rd and 164th Sts	25	20	8	1,100	3.84
61st Rd between Woodhaven Blvd and 85th St	25	7	8	500	2.96
149th St between 15th Rd and 16th Rd	25	6	8	500	2.53
247th St from 88th Rd to 89th Ave	25	6	8	700	1.81
40th Rd between College Point and Delong St	25	7	8	900	1.64
9th St between 38th and 40th Ave, 21st St between 34th and 40th Ave, Vernon Blvd between 34th and 40th Ave, 38th Ave between Vernon Blvd and 21st St	25	44	8	6,500	1.43
60th St between 50th Ave and Tyler Ave, 61st St between 50th Ave and Tyler Ave, 63rd St between 50th Ave and Tyler Ave, 64th St between 48th Ave and Tyler Ave	25	24	8-12	3,600	1.41
Beach 91st St between Rockaway Blvd and Holland Ave, Beach 92nd between Rockaway Blvd and Beach Channel Dr	25	9	8	1,500	1.27
13th Ave between 145th Pl and 147th Sts	25	6	8	1,000	1.27
35th Ave between Prince St and Linden Place	25	5	8	900	1.17
Pipes Probably Needing Replacement					
86th Ave between Commonwealth Blvd and 253rd St	25	12	12	2,200	1.15
Quince Ave between Robinson St and Oak Ave	25	8	8	1,500	1.13

(Continued)

* Breaks per year per mile.

(Sheet 1 of 3)

Table 12 (Continued)

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate
Pipes Probably Needing Replacement (Cont.)					
86th St between 78th Ave and Union Turnpike	25	4	8	800	1.06
43rd St between 55th Ave and 57th Ave	25	8	12-24	1,600	1.06
31st St between 48th Ave and Queens Blvd, 47th Ave between 28th St and 32nd Pl	25	7	8-12	1,500	0.99
69th St between 49th Ave and Garfield Ave, and 49th, 50th, and Garfield Ave one block on either side of 69th St, and Maurice Ave and Calams Ave from 67th St to 70th St	25	10	8-12	2,200	0.96
81st St between 149th Ave and 155th Ave, Sapphire St from 155th and 156th Ave	21	10	8	2,700	0.93
138th St between 29th Rd and 31st Dr	21	3	12	900	0.84
79th St between Eliot Ave and 62nd Ave	25	3	8	800	0.79
Bayview Ave and Broad St Area	25	8	8	2,200	0.77
84th St between Astoria Blvd and 30th Ave	25	4	8	1,200	0.70
Bell Blvd between 35th Ave and 43rd Ave	25	7	8	3,000	0.49
98th St between 25th Ave and 32nd Ave	25	5	8	2,200	0.48
Railroad Ave from Greenpoint Ave to end, Review Ave between 34th St and 37th St, Van Dam St between Star Ave and Newtown Creek, Greenpoint Ave between Star Ave and Review Ave	25	5	12	2,800	0.38

(Continued)

(Sheet 2 of 3)

Table 12 (Concluded)

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate
		Pipes Probably Needing Replacement (Cont.)			
44th St between Newton Rd and 34th Ave	25	3	8	1,800	0.35
10th St between 40th Ave and 41st Rd, 41st Ave between Vernon Blvd and 12th St	25	3	8-12	2,200	0.29

(Sheet 3 of 3)

including indirect cost, or inclusion of indirect cost makes the project justifiable.

89. Tables 11 and 12 can assist the Bureau of Water Supply in locating pipes needing replacement. However, not all projects may be needed. For example, some bad sections of pipe may already have been replaced within a project area such that the break rate of the remaining pipes is virtually zero. The Bureau of Water Supply must check to ensure that they have not already corrected the problems for which replacement is recommended as a solution. If construction activity was the cause of some of the breaks in a project area and that activity has ceased, the break rate can also be expected to decrease.

90. This report does not give the exact boundaries of the pipes to be replaced in each project because the break data provided at the beginning of the study were not of sufficient detail to locate pipe breaks at a specific address in most cases. For this reason, project lengths are only given to the nearest 100 ft. The precise boundaries of the replacement project must be determined by the Bureau of Water Supply.

Remedial Measures for Large Pipes

91. No large pipes are slated for replacement in Tables 11 and 12 because the replacement cost for large pipes (>24 in.) is so great. This does not mean that there were no large pipes with high break rates, but that the critical break rates for replacement of large pipes are very high. Large pipes with high break rates are given in Tables 13 and 14.

92. As described in Part II of this report, large pipes in New York City are generally made of steel and tend to experience corrosion holes rather that circular or longitudinal breaks. This situation suggests that a remedial measure other than replacement could reduce the number of breaks. Corrosion of large, welded steel pipes can be significantly reduced using cathodic protection. This type of protection can cost less than 10 percent of the cost replacement and should be investigated for pipes which show a susceptibility to corrosion.

93. A detailed corrosion survey of large mains will be required before installing cathodic protection. First, it will be necessary to identify if the cause of the corrosion problem is stray direct current. If that is the

Table 13

Large Pipes in the Bronx with Potential Need for Remedial Measures

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate*
Southern Blvd between E179th St and Tremont Ave	25	3	36	1,891	0.57
E. Gun Hill Rd between Bronx Blvd and Holland Ave	25	5	48	2,000	0.53

* Breaks per year per mile.

Table 14

Large Pipes in Queens with Potential Need for Remedial Measures

Pipe Location	Years	Breaks	Diam. in.	Length ft	Break Rate*
41st St between 19th Ave and 20th Ave, 19th Ave between Steinway St and 41st St, and Steinway St between 20th Ave and Berrian Blvd	25	20	60	2,000	2.11
91st St between 31st Ave and 32nd Ave	25	4	48	600	1.41
Astoria Blvd between 70th St and 72nd St, 70th St between Ditmars Blvd and Astoria Blvd, and Ditmars Blvd between 47th St and 70th St	25	11	48	2,300	1.01
37th Ave between 54th St and 57th St	25	4	48	1,000	0.84

* Breaks per year per mile.

case, the corrosion problem should be corrected by locating the source of the current and breaking the circuit. This could solve the problem and eliminate the need for cathodic protection. However, if the problem is due to corrosive soils rather than stray current, cathodic protection may be necessary. Before pursuing either course, the Bureau of Water Supply should inspect sections of the pipe to determine whether the pipe is so badly corroded that it is not worth saving.

94. Most of the larger pipes with high break rates are located in Queens, which reflects the more corrosive soils in that borough when compared with the more rocky subsurface of the Bronx.

Replacement of Small Pipes

95. Conspicuous in their absence from Tables 11 and 12 are small pipes (<8 in.) which were identified in Part II as having the highest break rates in the City. They were not included in the evaluation because of a policy decision by the Bureau of Water Supply to eliminate these small pipes due to their low beam strength and hydraulic carrying capacity.

96. The Bronx and, to a greater extent, Queens still have a considerable amount of small pipe in place. It will take several years to replace all of this pipe. Such work can be done most expediently during street rehabilitation.

97. Some sections of small pipe have experienced a very high incidence of breaks. For that reason, the Bureau of Water Supply may choose to make replacement of this subset of small pipes a high priority. Pipe segments experiencing more than two breaks during the 25-year period covered by the break inventory are listed in Tables 15 and 16. Due to the way in which the break data were reported, it was difficult (when two streets were reported for a break) to determine the street on which the pipe broke.

Other Rehabilitation Considerations

98. The observant reader will have noticed that the above procedure only considered three of the ways in which pipes age (main breaks, lost or inoperative valves, and leaks) and did not include a fourth important sign of an old pipe (loss of internal carrying capacity). The above procedure only

Table 15

Small Pipes with Three or More Breaks in the Bronx

Location	No. of Breaks Between 1955-1979	Diam.	Year Laid
Intersection of De Reimer Ave and Bassett Ave	4	2	1957
Intersection of Palmer Ave and Stillwell Ave	4	2	1925
Intersection of Schofield St and City Island Ave	3	6	1933
Intersection of De Lavall Ave and New England Thwy	4	6	1944
Intersection of E221st St and Bronxwood Ave	3	6	1904
Intersection of Barnes Ave and E214th St	3	4	1941
Intersection of E198th St and Decatur Ave	3	6	1895
Intersection of Palisade Ave and Ladd Rd	5	6	1880
Intersection of Anthony Griffin Pl and E144th St	3	6	1899
Intersection of Park Ave and E149th St	3	6	1895
Intersection of Commerce Ave and Ellis Ave	4	6	1957
Intersection of Commerce Ave and Newbold Ave	3	6	1957
Intersection of Park Ave and E149th St	3	6	1895
Intersection of W182nd St and Davidson Ave	3	6	1901

Table 16

Small Pipes with Three or More Breaks in Queens

Location	No. of Breaks Between 1955-1979	Diam.	Year Laid
Broadway between Bridge St and Church St	11	4	1962
16th Rd between 149th St and Murray St	10	6	1928
72nd St between 52nd Ave and 53rd Ave	8	6	1937
Intersection of 5th St and 47th Ave	7	6	1939
23rd St between Astoria Blvd and 25th Rd	5	6	1948
Intersection of Beach 14th St and Seagirt Blvd	5	6	--
Intersection of 1st St and 27th Ave	4	6	1951
Beach 41st St between Beach Channel and Rockaway Beach Blvd	4	2	--
25th Rd between 21st St and 22nd St	3	6	--
80th St between Juniper Valley Rd and Metropolitan Ave	3	6	--

considers the structural integrity of the pipes and as such is only the first step in the evaluation of rehabilitation alternatives for a water distribution system.

99. The next step would consist of evaluating the flows and pressures in the system, usually with a computer model of the system. Pipes which have not been marked for replacement in the above analysis can be considered for paralleling or cleaning and lining. The diameter of pipes marked for replacement may be changed from that of the old pipe based on flow requirements. Some rules for deciding when to clean and line pipes are presented in Walski (1984).

100. The key to making a fair evaluation of water system rehabilitation is to quantify in monetary terms all costs and benefits and to explicitly describe those that cannot be quantified. An overall procedure for making water system rehabilitation decisions is described in Walski (1986).

101. Missing from the above analysis are the costs of hydrants and hydrant lateral maintenance and replacement. Hydrants should be evaluated

separately since, if a hydrant is in good condition, it should be left in place even if the main is replaced; if it is in bad condition, it should be replaced even if the main is in good condition.

102. Hydrant laterals may be included in the pipe replacement analysis. If they are, their costs need to be included in C_r and their breaks, and leaks need to be included in J_0 and Q_0, respectively (See Appendix A).

Budget Estimate for Replacement Projects

103. For budgeting purposes, the following section gives the estimate of costs to replace the sections of pipe identified earlier. The lengths of pipe in each category were summed, and the unit prices presented in Appendix A were used to determine the investment requirements. The results are shown in Tables 17 and 18. For the purpose of these calculations, it was assumed that pipes would be replaced by pipes with the same diameter. The actual replacement pipe diameter should be based on an evaluation of the carrying capacity of the mains in that vicinity as compared with the required carrying capacity in that area.

PART IV: SUMMARY AND CONCLUSIONS

105. As is the case with any other water utility, the water distribution systems in the Bronx and Queens are deteriorating over time. This deterioration manifests itself in several ways, the most dramatic and costly of which are pipe breaks.

106. The overall water main break rates in the Bronx and Queens are 0.0746 and 0.0558 break/year/mile, respectively. These rates are consistent with many other communities, including Brooklyn and Staten Island, but are lower than in Manhattan where pipes are generally subject to more severe external loading.

107. Smaller pipes tend to experience more circumferential breaks; these breaks are indicative of inadequate beam strength for the external loads imposed. Large steel water transmission pipes tend to be more susceptible to corrosion holes. Corrosion tends to be the more common cause of breaks in Queens than in the Bronx, which tends to have more beam breaks. This is a reflection on the somewhat different subsurface conditions in the two boroughs.

108. Smaller diameter pipes also tend to break at higher rates than larger pipes. Six-inch pipes have the highest break rates, with 8-in. pipes clearly second in break rates. There is little difference among the larger sizes. This high break rate supports the Bureau of Water Supply's policy of replacing 6-in. pipe when convenient.

109. Pipes tend to break at much higher rates during cold weather, apparently due to extra loading caused by frost penetration. This is especially true for smaller pipes.

110. The overall rate of pipe breakage is increasing with time. This is due primarily to gradual deterioration of pipe over time. However, these effects are somewhat masked by variations in pipe material and laying practices over the history of the system.

111. It is possible to derive rules, based on sound economic principles, to indicate which pipes should be replaced. Such an equation can be used to determine a "critical pipe break rate." If a pipe break rate is higher than the critical break rate, it should be replaced. Otherwise, it should continue to be repaired when it breaks. The critical break rate will depend on many factors, most notably the pipe diameter. Unfortunately, the

data used to calculate the critical break rate are imprecise. As such, the critical break rates are merely indicators of which pipes should be replaced. The least certain value used to calculate the critical break rate is the indirect cost of a pipe break. Because of the uncertainty of this parameter, a range of critical break rates was given.

112. Since 6-in. pipes are already slated for replacement, they were not considered in the analysis. However, a list of 6-in. pipes with very high break rates was prepared.

113. In general, large pipes (>24 in.) were not identified as candidates for replacement because of the very high installation costs. Nevertheless, some have fairly high break rates. Most of these breaks, however, are corrosion holes; elimination of stray direct current and cathodic protection appear to be much more promising remedial measures than replacement.

114. Recommended replacement costs will run about $5 million in each borough. While this amount is fairly large, each borough is spending roughly $1 million in direct pipe break costs each year (neglecting damages and indirect costs), and that value is increasing. The pipes identified for replacement have break rates roughly 10 times the borough average so that their replacement should reduce repair costs.

115. Overall, there are no dramatic problems with the water supply infrastructure in the Bronx and Queens. There are, however, savings to be realized by identifying and replacing poor sections of the distribution system, as identified in this report.

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APPENDIX A: DEVELOPMENT OF REPLACEMENT RULES FOR PIPES

Background

1. As pipes age, their breakage rate tends to increase and they become more likely candidates for replacement. Usually the decision to replace a water main is a judgment made by the utility's engineering personnel. However, it is possible to develop rules based on the fundamentals of engineering economics to help decide when to replace a pipe.

2. The first such rules were developed by Shamir and Howard (1979).* Similar rules were developed and applied by the US Army Engineer District (USAED), New York (1980, 1984), Walski and Pelliccia (1982), and Weiss et al. (1985). All of the above rules involve a comparison of the present worth of the cost to replace the pipe with the present worth of future costs of breaks. It is assumed that the costs of replacement and breaks, which include indirect break costs, are the only major cost items.

Purpose

3. The purpose of this appendix is to present an improved rule for determining when to replace water mains due to leakage, pipe breaks, and inoperative valves. The rules can assist water utility engineers with justification for replacement of water mains rather than basing such decisions primarily on judgment.

4. The rules are presented in their most general form first, followed by some simplified versions. Next, guidance is provided to assist engineers in determination of the numerical values for the parameters that must be used in the equations. An example is then presented, followed by a discussion of how these rules fit into the overall framework of water system rehabilitation decisionmaking.

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* See References at the end of the main text.

Cost Items

5. The costs involved with replacing a water main versus maintaining an old one can be broken into: (a) replacement cost, (b) breakage cost (including indirect break cost), (c) water loss due to leakage, (d) leak detection and repair cost, and (e) valve maintenance.

6. The replacement cost refers to the new (replacement) pipe, while the other cost items refer to the difference in cost between the old and new pipe. In most instances, due to improved pipe materials and joints and construction practices, the maintenance cost of new pipes will be negligible when compared with that of existing pipes. Therefore, what is called leakage rate or breakage rate is actually the difference between old and new pipe and can be approximated by the leakage and breakage rate of the old pipe. Each cost item is described below.

Replacement cost

7. Replacement cost (in dollars) is simply the product of the unit cost of pipe (including valves and indirect cost) and the length replaced:

$$\text{Replacement} = 5{,}280\ C_r L \qquad \text{(A1)}$$

where

C_r = unit cost of replacement, \$/ft

L = length of pipe under consideration, miles

Breakage cost

8. Annual breakage cost (dollars per year) in year t can best be described by an exponential growth model (Shamir and Howard 1979, Walski and Pelliccia 1982) and can be given by:

$$\text{Breakage cost} = C_b L J_0 \exp\ (bt) \qquad \text{(A2)}$$

where

C_b = cost of a break, \$

J_0 = break rate in year 0, breaks/year/mile

b = annual increase in break rate, fraction/year

Water loss due to leakage

9. The annual cost of water lost due to leakage can be given by a similar exponential function:

$$\text{Leakage cost} = C_w L Q_0 \exp(at) \qquad \text{(A3)}$$

where

C_w = value of water lost to utility, \$/Mgal

Q_0 = leakage rate in year 0, Mgal/year/mile

a = annual increase in leakage rate, fraction/year

Leak detection and repair

10. Leak detection and repair cost is a function of both the size of the system and the number of leaks, and if detection is an ongoing practice, should not increase with time. The annual cost for leak detection and repair can be represented by a function of length only as:

$$\text{Leak detection and repair} = C_d L \qquad \text{(A4)}$$

where C_d = unit cost for leak detection and repair, \$/mile.

Valve maintenance

11. The cost of a broken or lost valve is actually realized in the large amount of time required to shut down a portion of the system for repair and the larger areas of the system that must be left without service due to maintenance work. Since these costs cannot be approximated well, they can be replaced by the cost to replace the broken valve in the existing pipeline. This cost will be a function of diameter, and the number of broken valves should increase with time in a similar manner as the pipe break rate (i.e., exponentially). This cost can be given by:

$$\text{Annual cost of broken valves} = C_v L V_0 \exp(vt) \qquad \text{(A5)}$$

where

C_v = cost to replace a broken valve in an existing pipe, \$

V_0 = valve break rate in year 0 , broken valves/mile/year

v = annual increase in valve break rate, fraction/year

Derivation of Replacement Rule

12. If a pipe is replaced in a given year T , the total cost of that pipe over the planning horizon can be given as the sum of the present worth of all the above-described costs. Compounding the interest rate continuously at interest rate r and treating the present worth of maintenance cost of the new (replacement) pipe as negligible (i.e., maintenance cost = 0 for $t \geq T$) gives the total costs as

$$C(T) = 5{,}280\ LC_r \exp(-rT) + \int_0^T \Big\{ (C_b L J_0) \exp[(b - r)t]$$

$$+ \ (C_w L Q_0) \exp[(a - r)t] + C_d L + C_v L V_0 \exp[(v - r)t] \Big\} dt \qquad \text{(A6)}$$

where r = interest rate expressed as a fraction.

13. The goal of this analysis is to find the value of T that minimizes the present worth of all future costs. This can be done by differentiating Equation A6 by T and setting the results equal to zero:

$$0 = -5{,}280\ rC_r L \exp(-rT) + C_b L J_0 \exp[(b - r)T] + C_w L Q_0 \exp[(a - r)T]$$

$$+ C_d L \exp(-rT) + C_v L V_0 \exp[(v - r)T] \qquad \text{(A7)}$$

14. To determine the optimal year to replace a pipe, all that must be done is calculate T from the above equation. The problem is that it is not possible to solve Equation A7 explicitly for T . It is possible, however, to multiply Equation A7 by $\exp(rT)/L$ and solve for one of the T values. Since break costs are usually the largest item, Equation A7 will be solved for that T , although it is possible to solve for any other T . This gives a formula that can be solved iteratively for T :

$$T = \frac{1}{b} \log_e \left[\frac{5,280 \ rC_r - C_w Q_0 \exp(aT) - C_v V_0 \exp(vT) - C_d T}{C_b J_0} \right] \quad (A8)$$

Special Cases

15. Variable T appears in several places in Equation A8 and must be determined by trial and error. Some simplification of the equation can be made for special cases to give equations that can be explicitly solved for T . The first case is when the rate of increase of breaks, broken valves, and leaks is roughly the same ($a = b = v$), which is a reasonable approximation for most systems, especially those with no ongoing valve exercising or leak detection program ($C_d = 0$). In this case, the year to replace the pipe can be given by:

$$T = \frac{1}{b} \log_e \left(\frac{5,280 \ rC_r}{C_b J_0 + C_w Q_0 + C_v V_0} \right) \quad (A9)$$

16. Another special case occurs in utilities which conduct routine leak detection and repair. In this case, the leakage rate should remain roughly constant over time ($a = 0$) since leaks are repaired at roughly the same rate at which they occur. If leak detection and repair will cost C_d (\$/year/mile) and will be conducted only for old pipes, and, again assuming $a = b = v$, Equation A8 becomes

$$T = \frac{1}{b} \log_e \left(\frac{5,280 \ rC_r - C_d - C_w Q_0}{C_b J_0 + C_v V_0} \right) \quad (A10)$$

17. It is possible for the value of T in the above equations to be negative. This means that the pipe should already have been replaced. A special case for which the above equations will not work is that in which a , b , and v are all zero. This implies that breaks and leakage are not increasing with time. In this case, if the pipe is to be replaced, it is economical either to replace it immediately or never. Therefore, instead of solving for the year T , the engineer would simply compare the cost of replacing the pipe now versus the present worth of all future leakage, breakage, and

detection. The resulting rule states that a pipe should be replaced if:

$$5{,}280\ rC_r < C_b J_0 + C_v V_0 + C_w Q_0 + C_d\ , \text{ for } a = b = v = 0 \qquad \text{(A11)}$$

18. Equation A9 can be rewritten assuming C_d is small to give some insights into the factors being considered as

$$T = \frac{1}{\text{Deterioration rate}} \log \left(\frac{\text{Annualized replacement}}{\text{Annual O\&M cost}} \right) \qquad \text{(A12)}$$

If the annual operation and maintenance (O&M) cost is high or the pipe is deteriorating rapidly, the pipe should be replaced soon. However, if the replacement cost is high relative to the O&M cost or the pipe is not deteriorating rapidly, replacement can be delayed well into the future.

19. Instead of solving Equation A9 for T, the optimal replacement year, one can solve Equation A9 for the current break rate J_0. Then, by selecting a value of T, a critical break rate J^* can be determined. It is called the critical break rate because pipes with a higher break rate should be replaced by year T, while pipes with a lower break rate need not be replaced. This relationship can be given as

$$J^* = \frac{[(5{,}280\ rC_r - C_d) \exp(-bT) - C_w Q_0 - C_v V_0]}{C_b} \qquad \text{(A13)}$$

where J^* = critical break rate, breaks/years/mile.

20. Other special cases can be identified, but the above equations should give rough rules of thumb for deciding when to replace a pipe. As with any decisionmaking rules, the results are only as reliable as the data used to obtain them. The next section describes how an engineer can collect data to use the equations.

Required Data

21. Most of the parameters in the above equations describe quantities that are virtually impossible to measure directly. While this is discouraging to most engineers who like to work with quantities that can be measured accurately (e.g., pressures, flows), it is not as serious an indictment as one might initially think, for two reasons. First, the logarithm of most of the variables is taken in the calculation of T. This means that inaccuracies in the cost and break rate data are only significant if they are large. Second, the engineer must realize that the values for replacement year T are only indicators of the ideal replacement year. For example, if $T = 13.25$ years, the pipe should be replaced somewhere between 10 and 15 years in the future, not necessarily 13 years and 3 months. Replacing large amounts of pipe at a single time also tends to lower unit costs.

22. Methods to determine each of the parameters used in the analysis are described below.

Unit cost of replacement

23. The unit cost to replace C_r should include all costs, such as engineering and design, supervision and inspection, reconnecting service lines, and removing or capping abandoned pipe, and should be based on the historical record of pipe replacement in the immediate area.

24. Because of population density, traffic congestion, interference with other buried utilities, high labor cost, and use of fairly thick-walled pipe, pipe replacement costs in New York City are somewhat higher than the national average. While the cost of laying pipe will vary throughout the City due to site-specific conditions, for the purpose of this study, costs will be treated as a function of diameter alone since diameter is the most important determinant of cost. Typical costs for pipe replacement (including hydrant replacement) in 1986 were provided by the Bureau of Water Supply and are listed in Table A1.

Cost of a break

25. The cost of a break C_b should include all costs, including repair, damages, interference with other utilities, traffic interruptions, etc. Walski (1985) presents data on repair costs. Damage costs can be approximated by claims against the utility for past damages. Other indirect

Table A1

Unit Costs for Pipe Replacement

Diameter in.	Unit Cost Per foot	Per mile
8	90	475,000
12	105	554,400
20	150	792,000
24	300	1,584,000
36	600	3,168,000
48	1,000	5,280,000
60	1,500	7,920,000
72	2,000	10,560,000

costs can only be roughly estimated but should nevertheless be included to give a fair evaluation.

26. The direct repair cost of a water main break in New York City can be estimated from the overall repair cost budget. Out of sampling of 391 "complaints" received during FY 1985, 333 were attributed to joint, service, hydrant, or valve leaks. The remaining 58 of the 391 (15 percent) were due to main breaks. The personnel services cost for repair work during that 1-year period was $25,186,000 with an additional $3,109,000 for materials and equipment. Fifteen percent of this value is $4,244,000. Operation and maintenance cost of the "water main break fleet" was estimated at $190,000 while the annualized vehicle cost was $152,000. This gives a total cost of $4,586,000. Utility overhead was not included.

27. During this time, there were 533 water main breaks. This results in a unit cost of $8,600 per main break. This value is probably somewhat low since, while main breaks correspond to 15 percent of the repair events, they are probably more costly events than service or hydrant leaks. While $8,600 is an average cost, the cost of an individual break will vary depending on the size of pipe, type of repair required (e.g., corrosion hole patch, repair clamp, replace section), and the ease of shutting down the broken section.

28. While the above costs reflect the cost to the Bureau of Water Supply to repair a break, some costs of a break are borne directly by

individuals (or businesses) or by society as a whole. Costs to individuals can be approximated by damage settlements resulting from main breaks since individuals affected by breaks are likely to try to recover costs from the utility. The Brooklyn Infrastructure Report (USAED, New York 1984) gives the following average settlement costs as a function of diameter:

Diameter, in.	Average Settlement per Break, $
6-8	2,700
12	6,000
16-20	8,000
24-48	14,000

The above values should also be realistic for the Bronx and Queens. This raises the average cost for a main break to approximately $20,000. Other costs borne by society as a whole include traffic control, delays, disruption of water service, loss of fire-fighting capacity during shutdown, minor damages not sufficient to make a claim against the utility, disruption of businesses, and interference with other utilities. These costs can be even greater than the repair and damages cost. For calculating the critical break rates of pipes, values of 0 and $40,000 will be used to determine the sensitivity of critical break rates to this value.

Break rate

29. The current break rate J_0 can be determined from records of breaks in that type of pipe in that utility. Of all the parameters in Equation A7, J_0 has the greatest variability as it can vary by orders of magnitude within a given utility. Therefore, a fairly detailed analysis of historical breaks in a neighborhood or problem area is a necessary part of a pipe replacement evaluation.

Annual increase in break rate

30. The rate of increase of pipe breaks b is one of the most critical parameters since it is outside the log expression in the equations for T. It can be determined by plotting breaks per year per mile versus age of pipe, for a given type of pipe, on semilog graph paper (breaks on log scale). The data will show a great deal of scatter due to such things as severe winters or wet years for expansive soils. The engineer should not expect the data to

fall exactly on the line and may need to use some statistical technique such as plotting 5-year moving averages to smooth the data. From past studies, pipe break rates appear to increase on the average from 1 to 6 percent per year (i.e., $0.01 < b < 0.06$).

31. Data presented in Part II of this report indicate that the break rate in the Bronx and Queens is increasing at a rate of approximately 2 percent per year due to pipe deterioration. This value will be used in the economic analysis.

Value of water lost to utility

32. The value of water to be saved represents the savings (in dollars per million gallons) to the utility realized by preventing leaks. This is not necessarily the price of water to consumers since that cost includes overhead items and administrative costs which are independent of flow. If a utility purchases all of its water from another utility at adequate pressure and quality, that price can be used as the value of water. If a utility has adequate capacity, the savings will only come from reduction in pumping energy and chemical costs. If the utility is planning capacity expansion, then the savings should be based on the sum of energy and pumping energy savings plus savings in construction costs of additional capacity. More details on valuing lost water are provided in Walski (1983).

33. New York is currently expanding its water transmission tunnel system. This construction project means that the value of water will be significantly greater than the cost of treating and pumping the water, which for New York City is relatively small. The size and life of the new transmission tunnels are affected by the quantity of water lost. However, it would be difficult to quantify the impacts. For the purposes of this study, it was felt by the Bureau of Water Supply that the cost of water to the consumer would be a good indicator of the value of water. In 1986, the City of New York is charging $0.725 cents per 100 cu ft or $969 per million gallons to its largest customers. This value will be used during the study.

Leakage rate

34. The leakage rate Q_0, in million of gallons per year per mile, can most accurately be determined from the results of a water audit of the area under consideration. If this value is not available, the leakage rate can be estimated based on the size and frequency of past leaks. A third (and least

accurate) method of estimating this value is to estimate leakage based on unaccounted-for water minus unmetered use, divided by miles of pipe.

35. The leakage rate in New York City can be estimated based on the results of ongoing leak detection surveys. During 1985, 17.1 Mgal/day of leakage was detected in 1,315 miles of pipe surveyed. This converts to a leakage rate of 4.75 Mgal/year/mile. (The actual leakage may be considerably higher than detected leakage, so this should be considered a conservative estimate.) When this is combined with the value of water lost ($969/Mgal), the Bureau of Water Supply is losing water at a rate of $4,600/year/mile. Of course, this value will be considerably higher for older pipes with poor joints and much lower for new, properly installed pipe.

Annual increase in leakage rate

36. The rate of increase of pipe leakage a is a number that must usually be estimated since most utilities do not conduct water audits annually to determine a trend, and utilities that do would probably repair the leaks regularly and have an a value of zero. The rate of increase of breaks b would appear to be a reasonable estimate of rate of change in leakage.

Unit cost for leak detection and repair

37. This cost, C_d, in dollars per year per mile, can best be estimated from the cost of past programs for that utility. Cost for detection can range from a few hundred to a few thousand dollars per mile. Cost for repair can be estimated from the average number of leaks per mile times the cost to repair a single leak. Moyer et al. (1983) provide some data on cost of such a program. The detection and repair costs can be divided by the time interval between surveys to determine an annual cost. When a utility does not conduct leak detection, the value of C_d is zero and can be ignored in the analysis. In such cases, the value of Q_0 and a will be relatively high.

38. New York City uses its own personnel, vehicles, and correlators to conduct leak detection work. The cost to conduct leak detection work during the second half of FY 1985 and the first half of FY 1986 is presented in the tabulation below. The category OTPS stands for "other than personnel services."

Salaries	$1,123,000
Vehicles	122,000
Correlators	56,000
OTPS	15,000
Total annual cost	$1,316,000

39. Some of the costs are attributable to responding to complaints of leakage while others are attributable to routine surveys. Approximately 46 percent of the leaks located were in response to complaints, while 54 percent were located as a result of surveys. Since 1,315 miles of water main were surveyed, the unit cost for a mile of leak survey can be estimated as follows:

$$\$1,316,000\ (0.54)/1,315 = \$540/\text{mile} \qquad \text{(A14)}$$

40. Since the New York water distribution contains roughly 6,200 miles of pipe, the 1,315 miles surveyed during the year under consideration represent 21 percent of the system. At this rate, the entire system can be surveyed in a little less than 5 years. The cost of routine leak detection can therefore be estimated as:

$$\$540/\text{mile}\ (1,315\ \text{miles/year})/6,200\ \text{miles} = \$110/\text{miles/year} \qquad \text{(A15)}$$

41. Locating leaks is only the first step in stopping the leaks. Annual repair costs for FY 1985 are summarized below:

Salaries	$14,685,000
Vehicles	1,296,000
OTPS	1,860,000
Annual repair cost	$17,841,000

The above costs include major break repair and hydrant repair as well as leak repair. Leak repair was estimated to take up 30 percent of the man-hours for repairs of $5,352,000/year. The system contains roughly 6,200 miles of water mains. This makes the annual average leak repair cost for water mains $5,352,000/year/6,200 miles, or $863/mile/year.

Cost to replace
broken valve in existing pipe

42. The cost of a valve should be based on replacing a valve rather than the cost of installing a valve in a new pipe. This value, C_v , is highly dependent on the diameter of the pipe.

43. Costs for valve replacement were provided by the Bureau of Water Supply and are listed below. The costs are based on the assumption that labor, paving, and vehicle costs are roughly the same for all diameters. The variation is therefore due to differences in valve and pipe costs with diameter.

Diameter, in.	Valve Installation Cost, $
4	1,586
6	1,641
8	1,786
12	2,196
16	3,177
20	5,201

Valve break rate

44. The current rate of valve breakage in breaks per year per mile represents the rate at which valves are becoming inoperable. It can be based on the number of valves that need to be replaced each year. That number will be somewhat low since some broken valves are not detected. It is important to keep track of valve breakage as a function of diameter since even if valves break at the same rate for each diameter, there are usually more small valves per mile than large valves.

45. The rate at which valves break in a system is difficult to estimate accurately since many inoperative valves go undetected unless a utility has an active valve exercising program. The rate at which broken valves are replaced can serve as a lower limit for the rate at which they break. In New York City, 57 valves were replaced in 1984 while 73 were replaced in 1985 (an average of 65 per year). Most of these replacements were on 6-in. mains with 8-in. valves being the second most likely to be replaced. Since there are 6,226 miles of mains in the system, the rate of breakage can be estimated as 65/6,226 = 0.0104 broken valve/year/mile.

46. In comparison with the low estimate, one can develop a high estimate for the valve breakage rate by noting that in many utilities 1 out of every 10 valves are inoperative. The utility may be unable to find the valves or unable to operate them once they are found. Considering that there are usually about 10 valves per mile and that it may be 10 years between when a valve breaks and when it is replaced, the valve breakage rate may be as high as 0.1 broken valve/year/mile (1 break/mile over 10 years). This value is an order of magnitude greater than the value given above.

Increase in valve break rate

47. The rate of increase of valve breakage v can be determined by looking at past records of valve replacement to determine a trend. Note that, as in the case of determining b, valve breaks will not increase smoothly with time, as some years utilities will be more vigilant in tracking down broken valves. Nevertheless, there should be a trend over, say, a 10-year interval.

Interest rate

48. The interest rate r is the rate at which the utility will borrow money to accomplish the work. It should be expressed as a fraction (i.e., for an interest rate of 10 percent, $r = 0.10$).

49. At present, the interest rate at which the Bureau of Water Supply obtains money is 8 percent. However, since some of this interest rate is due to inflation, a case can be made for using an interest rate corrected for inflation (Shamir and Howard 1979). This can be done by dividing $(i - f)$ by $(1 - f)$ where f is the inflation rate and i is the nominal interest rate. In recent years the consumer price index, a useful indicator of inflation, has hovered at 3 percent. This is consistent with changes in the Engineering News Record Construction Cost Index. Therefore, f can be taken as 0.03. The corrected interest rate, which will be used in this study, is $0.05/0.97 = 1.051$, or 5 percent.

Optimal year to replace pipe

50. The parameter T is the year by which a pipe needs to be replaced to minimize costs. Since it will probably take a decade to make all of the replacements recommended in this report, a value of 10 years will be used for T when calculating the critical break rate.

51. Conspicuous in its absence from the above list is the length of pipe under consideration. This results from the fact that all costs and breakage

rates are given per unit length. Therefore, the above procedure should be applicable whether it is applied to a single city block or a major city. Of course, in applying the above procedure to a major city, spatial variation in unit costs would need to be taken into account.

52. From the above description of data required, it should be clear that a good deal of effort in quantifying costs and the magnitude of the leakage and breakage problem is required before one should attempt to determine the optimal replacement year or critical break rate.

Order of Magnitude Comparison

53. In some utilities, one or two of the individual cost items will be negligible. To save computational time, it will be worthwhile at the beginning of the evaluation to compare the order of magnitude of the costs to see if some can be ignored. For example, in a utility with annual pipe break costs $C_b J_0$ of $1,000 per mile per year and annual valve breakage cost $C_v V_0$ of $25 per mile per year, the valve breakage terms can be ignored in the calculations.

54. A comparison of costs for New York City is presented below to identify which of the maintenance cost items are most important and which can be neglected. Each major cost is determined on a dollars per mile per year basis using data presented above.

Break repair

55. Using an average breakage rate of 0.08 break/year/mile and an average break cost of $8,600 for direct utility costs, average annual break costs per mile are $688/year/mile.

Water loss

56. Using an average leakage rate of 4.75 Mgal/year/mile and a value of water of $969/Mgal, the annual value of leakage per mile can be estimated as $4,600/year/mile.

Leak detection and repair

57. Leak detection and leak repair costs were presented earlier as $110/year/mile and $863/year/mile, respectively. Their sum is approximately $1,000/year/mile.

Valve replacement

58. Using a valve breakage rate of 0.0104 broken valve/year/mile and an average valve cost of $2,000, valve replacement will be approximately $20/year/mile, a minor cost item when compared with the others above.

59. The order-of-magnitude of the various cost items is summarized below:

Item	Average Annual Cost ($/year/mile)
Break repair	688
Water loss	4,600
Detection and repair	1,000
Valve replacement	20

60. While the average values for the cost items are informative, the actual values for individual pipes vary widely. Some pipes have breakage rates of up to two breaks/year/mile over long periods of time so that their annual break repair costs can be as much as $17,200/year/mile. Similarly, repair unit costs can vary by a factor of two or three from one site to another.

61. Leakage costs also vary from one pipe segment to another because of the varying leakage rates throughout the system. While leak detection costs are fairly constant across the system, leak repair costs will depend on location.

62. Of all the factors affecting annual maintenance cost, break rate appears to be the one that varies most from one pipe to the next. This must be treated as a variable in making rehabilitation decisions. While break repair and leak repair unit costs do vary spatially throughout the system, it is not possible to perform cost estimates that reflect that spatial variation. Average cost will be used for those values. Similarly, there is no way to accurately predict the variation in leakage rates throughout the system for this type of study. Therefore, a constant leakage rate can be used.

63. The direct annual maintenance cost per mile of pipe will consist of leak detection and repair, and break repair and can be given by:

$$\text{Direct cost maintenance} = 8{,}600\ J + 1{,}000 \tag{A16}$$

where J = break rate for a given pipe, breaks/year/mile.

64. The City of New York also incurs costs due to water loss and damage claims. The cost of damages depends on the break rate and should be included in the breakage term, while the cost of water lost should be included with leak detection. Thus,

$$\text{Total direct cost} = (8{,}600 + C_d)\ J + 5{,}600 \qquad \text{(A17)}$$

where C_d = cost of damages, \$. In addition, there are many indirect costs that are borne by: (a) individuals who do not have a way of recovering the cost from the Bureau of Water Supply, or (b) society as a whole. These indirect costs can be added into the above equation to give the actual cost of maintaining water pipes as:

$$\text{Total cost} = (8{,}600 + C_d + C_i)\ J + 5{,}600 \qquad \text{(A18)}$$

where C_i = indirect cost of a break, \$.

65. The total operation, maintenance, and repair cost for the distribution system in dollars per year per mile contains the most important cost items and was used in the evaluations presented in the main text. It must be remembered, however, that the above values are for an average section of pipe. The evaluation of pipe replacement must be based on the difference between the maintenance cost for the existing and replacement pipes.

Determining Critical Break Rate

66. As presented in Equation A13, the critical break rate is a function of 10 parameters. However, most of them are relatively small (e.g., valve maintenance) or are constant (e.g., leak detection and repair). The two that vary most are the cost of replacement and the cost of a break. Both are a function of diameter, and the cost of a break is dependent on the allowance for indirect cost as described above.

67. Substituting the typical numerical values for New York into Equation A13 and simplifying the equation gives:

$$J^* = \frac{(216\ C_r - 5{,}400)}{C_b} \qquad \text{(A19)}$$

Equation A19 is used in the body of the report to determine the critical break rates for pipes.

Summary

68. By quantifying the true maintenance cost of old water mains, it is possible to develop sound, economically justifiable rules for deciding whether to replace water mains.

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